TUGAS AKHIR – TE145561

Perancangan dan Penerapan Driver Servo Valve pada Modul Elektro Hidrolik Servomechanism EHS 160

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Dosen Pembimbing
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PROGRAM STUDI KOMPUTER KONTROL
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FINAL PROJECT – TE 145561

Designing and Implementing Servo Valve Drivers in Electrical Modules Hydraulic Servomechanism EHS 160

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Surabaya 2018

PERNYATAAN KEASLIAN
TUGAS AKHIR

Dengan ini saya menyatakan bahwa isi sebagian maupun keseluruhan Tugas Akhir saya dengan judul "**Perancangan dan Penerapan Driver Servo Valve pada Modul Elektro Hidrolik Servomechanism EHS 160**" adalah benar-benar hasil karya intelektual mandiri, diselesaikan tanpa menggunakan bahan-bahan yang tidak diijinkan dan bukan merupakan karya pihak lain yang saya akui sebagai karya sendiri.

Semua referensi yang dikutip maupun dirujuk telah ditulis secara lengkap pada daftar pustaka.

Apabila ternyata pernyataan ini tidak benar, saya bersedia menerima sanksi sesuai peraturan yang berlaku.

Surabaya, 30 Juli 2018

Muhammad Fachrudin Al Fadani
NRP 10311500000030

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PERANCANGAN DAN PENERAPAN DRIVER SERVO VALVE
PADA MODUL EHS 160

TUGAS AKHIR

Diajukan Guna Memenuhi Sebagian Persyaratan
Memperoleh Gelar Ahli Madya Teknik
Pada
Departemen Teknik Elektro Otomasi
Fakultas Vokasi
Institut Teknologi Sepuluh Nopember

Menyetujui :

Dosen Pembimbing

KEMENTERIAN RISET, TEKNOLOGI, DAN PENDIDIKAN TINGGI
INSTITUT TEKNOLOGI SEPULUH NOPEMBER
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JUNI , 2018

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ABSTRAK

Servo valve hidrolik adalah *valve* yang berfungsi untuk mengatur oli yang akan masuk pada ruang hidrolik dan digunakan untuk mengendalikan arah dan besar pergerakan dari aktuator hidrolik suatu peralatan. Sistem hidrolik memiliki karakteristik, gaya yang kecil dapat digunakan untuk menggerakkan atau mengangkat beban berat dengan cara mengubah perbandingan luas penampang silinder. Saat ini *driver servo valve* dan *servo valve* pada modul elektro hidrolik yang ada di departemen Teknik Elektro Otomasi sedang mengalami kerusakan.

Modul *Elektro Hidrolik Servomechanism* (EHS 160) dapat dikendalikan menggunakan mikrokontroller dan rangkaian driver servo valve amplifier yang terdiri atas rangkaian *zero-span* dan rangkaian *push-pull* komplementer. Komputer sebagai memberi nilai set point akan memberi perintah kepada *mikrokontroller, mikrokontroller* yang mengeluarkan sinyal digital. Sinyal digital yang dihasilkan, diberi rangkaian pengondisi sinyal (*signal conditioning*) guna memberi sinyal perintah ke *servo amplifier*. Didalam *servo amplifier* terdiri atas rangkaian *Zero-Span* dan rangkain *push pull* komplementer yang digunakan mengatur arus yang akan keluar dari *servo amplifier* dengan range -100mA hingga +100mA pada resolusi tegangan -2 hingga +2v.

Perancangan dan penerapan *driver servo valve* hidrolik ini telah dapat digunakan untuk mengendalikan *servo valve* pada modul *Elektro Hidrolik Servomechanism* (EHS 160). Rangkaian zero-span yang bertugas mengkonversi tegangan masukan 0 V – 3,33 V tegangan keluaran -2 V hingga +2 V. Rangkaian *push-pull* komplementer yang digunakan sebagai penguat daya dan arus guna mengendalikan kinerja dari servo valve dengan arus yang dapat dihasilkan -85mA hingga +80mA.

Kata kunci : *Servo valve, signal conditioning,* hidrolik, *servomechanism*

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ABSTRACT

Hydraulic servo valve is a valve that serves to regulate the oil that will enter in the hydraulic chamber and is used to control the direction and magnitude of the movement of the hydraulic actuator of an apparatus. Hydraulic systems have characteristics, small forces can be used to drive or lift heavy loads by changing the ratio of the cross-sectional area of the cylinder. Currently the driver servo valve and servo valve in the existing electro hydraulic module in the Department of Electrical Engineering Automation is being damaged.

Electro Hydraulic Servomechanism (EHS 160) module can be controlled using microcontroller and driver servo valve amplifier circuit consisting of zero-span circuit and complementary push-pull circuit. The computer as giving the set point value will give the command to the microcontroller to issue a digital signal. The resulting digital signal, given a signal conditioning circuit to signal commands to the servo amplifier. Inside the servo amplifier consists of a Zero-Span circuit and complementary push pull circuits that are used to regulate the outflow of servo amplifiers with a range of -100mA to + 100mA at a voltage resolution of -2 to +2v.

The design and application of this hydraulic servo valve driver can be used to control the servo valve in the Electro Hydraulic Servomechanism (EHS 160) module. Zero-span circuit in charge of converting input voltage 0 V - 3.33 V output voltage -2 V to +2 V. Complementary push-pull circuit used as a power amplifier and current to control the performance of servo valve with the current that can be generated - 85mA to + 80mA.

Keyword : *Servo valve, signal conditioning, h*ydraulic, *servomechanism*

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KATA PENGANTAR

Alhamdulillah, segala puji syukur bagi Allah SWT karena berkat rahmatNya, penulis dapat menyelesaikan Tugas Akhir yang berjudul :

" PERANCANGAN DAN PENERAPAN *DRIVER SERVO VALVE* PADA MODUL ELEKTRO HIDROLIK *SERVOMECHANISM* EHS 160"

Pembuatan dan penyusunan Proyek Akhir ini diajukan sebagai salah satu syarat untuk menyelesaikan Studi Diploma III (D3) guna memperoleh Gelar Ahli Madya (A.Md) di Departemen Teknik Elektro Otomasi Institut Teknologi Sepuluh Nopember Surabaya.

Penulis berusaha dengan sekuat badan dan hati, segenap jiwa dan raga dengan segala keterbatasan, kebodohan dan kekurangannya sehingga dapat diselesaikannya laporan dan pengerjaan Proyek Akhir ini oleh karena atas berkat Rahmat Allah yang maha kuasa dan dengan di dorong oleh keinginan yang luhur serta banyak dibantu oleh berbagai pihak. Tak lupa penulis memohon ampunan dan maaf atas seluruh kesalahan yang selalu penulis perbuat.

Demikian besar harapan penulis, semoga laporan Proyek Akhir ini dapat bermanfaat bagi yang mau peduli ataupun tidak.

Surabaya, 30 Juli 2018

Penulis

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UCAPAN TERIMA KASIH

Kami sangat bersyukur atas berkat rahmatNya, hingga saat ini kami masih diberikan kesempatan untuk dapat mengenyam pendidikan yang tinggi sehingga kami dapat menyelesaiakn laporan serta pengerjaan Tugas Akhir ini. Kami haturkan doa dan rasa terimakasih ini, khususnya kepada :

1. Rasulullah sallallahu alaihi wasallam yang telah menuntun dari kegelapan hingga terang benderang, Dinnul Islam.
2. Kedua Orang Tua dan keluarga kami yang selalu dan setiap saat memberikan dukungan penuh.
3. Bapak Slamet Budi Prayitno, S.T., M.T selaku dosen pembimbing Tugas Akhir dari penulis
4. Bapak Ciptian Weried P. S.ST., M.T. ; Bapak Fauzi Imaduddin S.ST., M.T., ; dan Bapak Dwi Lastomo S.Si., M.T. selaku dosen penguji yang telah membimbing dalam penulisan buku tugas akhir penulis
5. Seluruh Bapak dan Ibu dosen, karyawan, dan tenaga didik yang telah membimbing dan membekali ilmu kepada penulis selama menempuh pendidikan di kampus Institut Teknologi Sepuluh Nopember Surabaya (ITS)
6. Seluruh keluarga HYDRA'15 angkatan 2015 Departemen Teknik Elektro Otomasi yang sudah saling membantu dan memberi semangat untuk menyelesaikan tugas akhir ini.
7. Untuk seluruh keluarga angkatan 2016 Departemen Teknik Elektro Otomasi yang sudah ikut membantu dalam pengambilan data dengan menyediakan alat – alat didalam Laboratorium saat proses pengambilan data.
8. Untuk teman saya yang telah menemani saya mencari referessi data dan buku petunjuk EHS 160 Ristina Dwi Yuliasari

9. Untuk teman yang selalu memberikan dukungan dan kopi saat penulis butuh inspirasi yaitu Indah Berliana Bening, Warih Rahman, Annora Prakoso, Rizky Fadhilla, Nadia Nuri.
10. Untuk teman yang selalu mendampingi saya dalam pengerjaan tugas akhir dan selalu berdampingan kemanapun pergi yaitu Ramadhani, Nuva, Imanda, Nashrudin L, Fajar Alif, Christian Agung, Dickry Junior, Amir M, Discha Ari, Wisnu Waskito, Ega Hasbi, Dwi Prasetyo, Mahfud K, dan Ronaldo Gabe.
11. Tak lupa bagi Pembaca Buku Proyek Akhir ini.

Besar harapan kami semoga Allah SWT selalu melimpahkan rahmatNya kepada seluruh pihak yang telah membantu terselesaikannya pengerjaan dan pembuatan laporan Tugas Akhir ini serta turut membantu pula dalam perkembangan kami selama studi di kampus ini untuk menjadikan kami insan yang berguna bagi sesama.

DAFTAR ISI

HALAMAN

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BAB I
PENDAHULUAN

1.1. Latar Belakang

Sistem hidrolik banyak digunakan untuk memindahkan beban yang berat atau sebagai alat penekan beban. Pada dunia industri sistem hidrolik digunakan sebagai sistem penggerak. Penggunaan sistem hidrolik pada alat-alat berat, seperti truk pengangkat (*dump truck*), *excavator*, mesin *moulding*, mesin tekan, mesin *flow forming*, *forklift*, *crane*, dan lain-lain. Sistem hidrolik memiliki karakteristik, gaya yang kecil dapat digunakan untuk menggerakkan atau mengangkat beban berat dengan cara mengubah perbandingan luas penampang silinder. Untuk penerapannya dibutuhkan kinerja dinamis yang baik sehingga diperlukan suatu sistem kontrol elektronik yang memiliki nilai yang baik.

Servo valve hidrolik adalah *valve* yang berfungsi untuk mengatur oli yang akan masuk pada ruang hidrolik dan digunakan untuk mengendalikan arah dan besar pergerakan dari aktuator hidrolik suatu peralatan

Servo valve hidrolik terdiri atas sistem kontrol loop tertutup yang terdiri dari sistem pengaturan posisi, pengaturan kecepatan, pengaturan aliran, dan *aktuator* hidrolik. Komputer sebagai memberi nilai *set point* akan memberi perintah kepada *mikrokontroller,* selanjutnya *mikrokontroller* yang mengeluarkan sinyal digital. Sinyal digital yang dhasilkan, diberi rangkaian pengondisi sinyal (*signal conditioning*) guna memberi sinyal perintah ke servo amplifier. Didalam *servo amplifier* terdiri atas rangkaian *Zero Span* dan rangkain *push-pull* yang digunakan mengatur arus yang akan keluar dengan skala arus sebesar -100mA hingga +100mA pada resolusi tegangan maksimum yang masuk pada *servo valve* -2v hingga +2v.

Departemen Teknik Elektro Otomasi mempunyai sebuah modul elektro hidrolik yang digunakan untuk kontrol posisi yang aktuatornya menggunakan *servo valve*. Modul ini bekerja dengan sistem kontrol loop tertutup. Kontroler pada modul digunakan untuk mengatur pembukaan jarum katub pada *servo valve* yang digunakan untuk mengatur tekanan oli guna menggerakkan motor hidrolik. Saat ini *driver servo valve* dan *servo valve* pada modul elektro hidrolik sedang mengalami kerusakan.

Perancangan dan penerapan *driver servo valve* hidrolik ini diharapkan dapat digunakan untuk mengendalikan *servo valve* dan aliran oli pada modul elektro hidrolik, sehingga dapat digunakan kembali untuk para praktikan.

1.2. Permasalahan

Permasalahan dalam penelitian ini adalah :

- Modul *Elektro Hidrolik Servomechanism* (EHS 160) belum dapat bekerja
- *Servo valve* dan motor hidrolik tidak dapat dikendalikan

1.3. Tujuan

Tujuan yang akan dicapai dari Tugas Akhir ini adalah sebagai berikut:

- Me-*retrovit* modul *Elektro Hidrolik Servomechanism* (EHS 160) agar dapat digunakan kembali untuk praktikum
- Mengendalikan *servo valve* agar dapat menggerakkan motor hidrolik sesuai kecepatan yang diinginkan

1.4. Metodologi

- **Pengamatan Permasalahan**

  Pada kegiatan ini penulis mendalami latar belakang, rumusan permasalahan, dan mengamati keadaan terkini terkait permasalahan pengendalian *servo valve* dengan kontrol elektronik.

Masalah lainnya adalah *servo valve* harus bekerja dengan frekuensi rendah secara terus menerus dapat memutus jarum. Permasalah ini diharapkan dapat menghasilkan solusi tepat untuk menyelesaikan masalah ini.

- **Study Literatur**

  Studi literatur merupakan tahap pencarian data dan literatur untuk mencari sumber-sumber yang relevan dan dapat dipercaya sehingga dapat memperkuat penulisan Tugas Akhir ini.. Literatur yang digunakan berasal dari jurnal, buku ilmiah, dan beberapa artikel dari internet. Materi mengenai spesifikasi dan perancangan *servo valve*, perancangan *driver servo valve,* dan perancangan rangkaian penguatan terhadap arus beban *servo valve.*

- **Perancangan Alat**

  Perancangan dan pembuatan alat driver *servo valve* ini akan me-*retrofit* modul elektro hidrolik yang ada di Departemen Teknik Elektro Otomasi ITS. Dalam pembuatan *driver servo valve*, digunakan beberapa rangkaian diantaranya rangkaian *mikrokontroler shield*, pengkondisi sinyal analog berupa rangkaian *zero-span* dan rangkain penguat arus. Selain rangkaian untuk *driver servo valve,* juga dirancang rangkaian pengkondisi sinyal analog untuk sensor yaitu dengan menggunakan rangkaian *inverting amplifier* . Dari rangkaian *driver servo valve* ini diharapkan dapat mengeluarkan arus -100mA hingga +100mA yang menggerakkan servo sesuai yang kita inginkan. Sensor berupa motor DC digunakan untuk pembacaan kecepatan motor hidrolik yang digerakkan oleh aliran oli.

- **Pengujian Alat**

  Pengujian dari *driver servo valve* ini terdiri atas 2 tahap yaitu tahap pengujian secara pengukuran arus yang dihasilkan driver servo dan tahap pengujian secara langsung dengan menggunakan modul elektro hidrolik

- **Kesimpulan**

  Untuk mengatur dan mengendalika *servo valve* rangkaian *driver servo valve* menggunakan rangkain *servo amplifier* yang terdiri atas rangkaian *zero-span* dan rangkain penguat arus berupa *push pull.*

- **Penyusunan Laporan**

  Tahap terakhir yang perlu dilakukan adalah penyusunan laporan yang bertujuan sebagai bukti tertulis bahwa pernah dilakukan penelitian mengenai hal ini.

1.5. Relevansi

Tugas akhir dibuat untuk menggerakkan *servo valve* dan mengatur aliran oli pada modul elektro hidrolik supaya modul tersebut dapat digunakan kembali untuk praktikum.

BAB II
TEORI PENUNJANG

Bab ini membahas mengenai teori dasar dari peralatan yang digunakan dalam "***Perancangan dan Penerapan Driver Servo Valve pada Modul Elektro Hidrolik Servomechanism (EHS 160)",*** antara lain modul elektro hidrolik servomechanism, servo valve, rangkaian op-amp, rangkaian zero-span, rangkaian *push-pull* komplementer, dan rangkaian modul DAC 12-bit.

2.1 Modul *elektro hidrolik servomechanism* EHS 160 [1][2]

Modul elektro hidrolik servomechanism EHS 160 diproduksi oleh Feedback corp dengan kode EHS160. Elektro hidrolik Servomechonism ditujukan untuk penggunaan eksperimental baik oleh siswa yang memulai studi mereka tentang sistem loop tertutup dan oleh mereka yang telah memahami esensi teori kontrol dan ingin mempelajari karakteristik yang khas untuk sistem hidraulik.

Tidak ada pengetahuan atau wawasan sebelumnya tentang sistem kontrol yang diasumsikan dalam buku teks. Namun, jika siswa terbiasa dengan subyektif, modul ini dapat membantu. Agar pemahaman yang lebih cepat dan lengkap dari materi yang diberikan di sini.

Setiap bagian dari karya eksperimental disertai oleh teori yang relevan Di mana pun teori ini, dari kebutuhan, terbatas secara mendalam, upaya dilakukan untuk memperkenalkan konsep-konsep penting.

Kontrol daya hidraulik merupakan bentuk paling umum dari manipulasi daya yang tepat yang digunakan dalam teknologi modern. Ini digunakan di seluruh pesawat, kapal, rool mesin, dan di setiap industri yang menggunakan kontrol otomatis hingga ratusan tenaga kuda.

EHS 160, yang dirancang khusus untuk pengajar teknisi dan insinyur mahasiswa, mewujudkan komponen hidraulik terbaru dan sirkuit elektronik dalam sistem komprehensif. Karena perhatian telah Diambil agar sesuai dengan demontrations dan pekerjaan eksperimental untuk persyaratan mahasiswa. Gambar 2.1 merupakan gambar modul elektro servomechanism EHS 160.

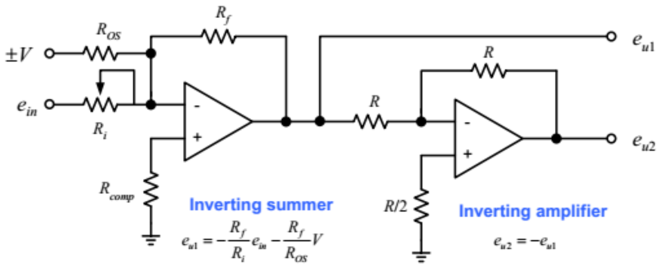
Gambar 2.1. Gambar modul *elektro hidrolik servomechanism* EHS 160.

2.2 Rangkaian Op-Amp [3]

Rangkaian Operational Amplifier atau di singkat rangkaian Op-Amp merupakan rangkaian yang menerima sinyal pada masukan (input) dan menghasilkan sinyal pada keluaran (output) yang berubah lebih besar amplitudonya. Rangkaian Op-Amp yang sering digunakan secara umum yaitu memiliki 2 rangkaian feedback (umpan balik) yaitu feedback negative (Inverting) dan feedback positif (Non Inverting) dimana Feedback negatif pada op-amp memegang peranan penting. Secara umum, umpan balik positif akan menghasilkan osilasi sedangkan umpan balik negatif menghasilkan penguatan yang dapat terukur (Pujiono : 2012).

2.3 Rangkaian Konverter *Zero-Span* [4]

Rangkaian *Zero-Span* adalah rangkaian converter yang dapat memungkinkan untuk menghasilkan parameter yang sesuai untuk tegangan yang diinginkan. Output suatu transducer jarang yang sesuai dengan pengkodisi sinyal atau display. Rangkaian pengubah *Zero-Span* dapat dibuat dengan menggunakan rangkaian penjumlah dan pembalik (*inverting summer amplifier).* Konsep dari konverter *Zero-Span* yang dapat direalisasikan dengan penguat inverting-summer (penguat penjumlah inverting) seperti pada gambar 2.1.



Gambar 2.2. Gambar Rangkaian dasar *Zero-Span*

Penguat ini mempunyai input 2 buah, yaitu :

(1) Vin merupakan yang tegangan masukan yang diberikan pada input inverting disambung seri dengan Ri, sebuah tahanan potensiometer, agar gain dapat diatur dengan mudah, Ein juga sebagai pengatur batas atas dari keluaran yang kita inginkan.

$$Gain = -\frac{Rf}{Ri} \text{ .... (2.1)}$$

(2) Tegangan referensi atau penguat Zero, diberikan dari tegangan V ±, yang disambung seri dengan Ros, sebuah potensiometer penguat zero offset, dengan gain :

$$Gain = -\frac{Rf}{Ros} \text{ .... (2.2)}$$

Dengan demikian maka tegangan Vout 1 adalah:

$$Vout\ 1 = -(Rf.Ri)Vin - (Rf.Ros) \text{ ......(2.3)}$$

Dari gambar 2.1 dapat pula diperoleh tegangan Vout2, yang merupakan kebalikan dari Vout1, yaitu :

$$Vout\ 2 = (Rf.Ri)Vin + (Rf.Ros) \text{ .... (2.4)}$$

Hal ini disebabkan oleh adanya gain dari penguat op amp kedua, sebesar gain = -1. Perbandingan persamaan Vout1 dan persamaan Vout2 dengan persamaan garis linier :

$$Y = mx + b \text{ .... (2.5)}$$

Dimana :

- m adalah gradien dari nilai span atau gain
- b adalah nilai batas dan batas bawah antara bilangan tengah output. Maka dapat didapatkan dari rumus

$$b = \frac{Rf}{Ros}Vreff \text{ ....(2.6)}$$

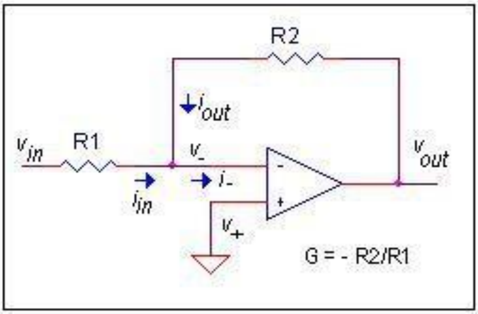
- Y adalah hasil perpotongan kurva sumbu Y Atau offset atau Zero

Dengan kata lain bila Vin = 0 (Zero), maka Eout = Rf/Ros V. Maka Vout dapat ditarik rumus sebagai berikut :

$$Vout = Vin\frac{Rf}{Ri} + Vreff\ \frac{Rf}{Ros} \text{ .... (2.7)}$$

2.3.1 Rangkaian Penguat Pembalik (*inverting amplifier*)

Rangkaian penguat inverting adalah rangkaian elektronika yang berfungsi untuk memperkuat dan membalik polaritas sinyal masukan. Rangkaian penguat inverting merupakan rangkaian penguat pembalik dengan impedansi masukan sangat rendah. Rangkaian penguat inverting akan menerima arus atau tegangan dari tranduser sangat kecil dan akan membangkitkan arus atau tegangan yang lebih besar. Rangkaian dasar penguat inverting adalah seperti yang ditunjukkan pada gambar 2.2, dimana sinyal masukannya dibuat melalui input inverting. Rangkaian ini adalah pengubah dari arus menjadi tegangan dan digerakkan oleh sumber tegangan dan bukan sumber arus. Pada rangkaian ini, umpan balik negatif di bangun melalui resistor R2.



Gambar 2.3 Gambar Rangkaian Penguat *Inverter*

Jika penguatan didefenisikan sebagai perbandingan tegangan keluaran terhadap tegangan masukan, maka dapat ditulis:

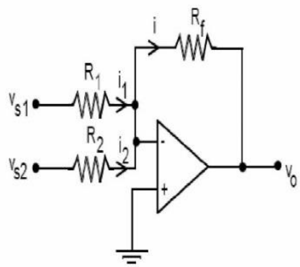
$$Gain = \frac{Vout}{Vin} = -\frac{R2}{R1} \text{ .... (2.8)}$$

Impedansi rangkaian inverting didefenisikan sebagai impedansi input dari sinyal masukan terhadap ground. Karena input inverting (-) pada rangkaian ini diketahui adalah 0 (*virtual ground*) maka impendasi rangkaian ini tentu saja adalah $Z_{in} = R_1$. Dari persamaan gain diatas dapat diketahui tegangan keluaranya sebagai berikut :

$$Vo(s) = -\frac{Rf(s)}{Ri(s)}\,Vi(s) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

2.3.2 Rangkaian Penguat Penjumlah (summer amplifier)

Rangkaian *Summing amplifier* digunakan untuk menjumlahkan beberapa sinyal *input* sehingga dihasilkan sebuah sinyal *output*. Sinyal *output* tersebut bisa berupa hasil penjumlahan matematis langsung dari sinyal-sinyal *input*, atau bisa juga mengandung penguatan (*gain*) tertentu. Dalam kasus dimana sinyal *output* merupakan hasil penjumlahan matematis langsung, semua resistor *input* dan resistor *feedback* berkisar antara 100-100kOhm. Pada gambar 2.3 adalah gambar rangkaian penguat pejumlah dengan contoh 2 sumber *input* tegangan pada *input* negatif (inverting amplifier)



Gambar 2.4 Gambar Rangkaian *Summing Amplifier*

Dalam kasus lain, yaitu apabila diinginkan adanya gain tertentu, maka resistor *feedback* dibuat lebih besar nilainya. *Summing amplifier* bisa juga berupa penjumlahan berskala (*scaling adder*), di mana resistor-resistor input nilainya ditentukan sedemikian rupa sehingga menghasilkan gain yang berbeda-beda untuk setiap input. Sesuai dengan kebutuhan, *summing amplifier* ini bisa dibuat dalam konfigurasi *inverting* maupun *non-inverting*.

Dalam rangkaian penguat penjumlah sederhana ini, tegangan keluaran, (Vout) sekarang menjadi sebanding dengan jumlah tegangan input, Vs1, Vs2, hingga Vs (n). Maka, kita dapat memodifikasi persamaan asli untuk penguat inverting untuk memperhitungkan input baru demikian persamaan penguat pembaliknya sebagai berikut :

$$Vout(s) = -\frac{Rf(s)}{Ri(s)} Vi(s) \text{ .... (2.10)}$$

Untuk menjadi penguat penjumlah maka diturunkan menjadi

$$-Vout = \left[\frac{Rf}{Ri}Vs1 + \frac{Rf}{Ri}Vs2 + \cdots \frac{Rf}{Ri}Vs(n)\right] \text{ .....(2.11)}$$

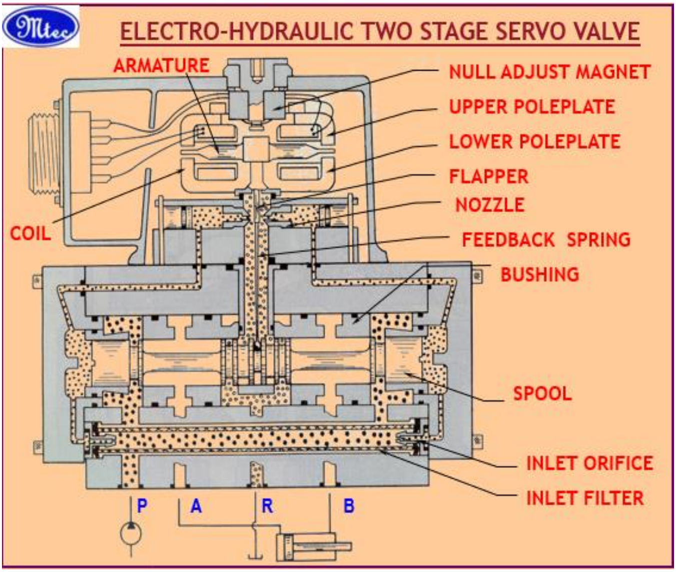
$$-Vout = \frac{Rf}{Ri}[Vs1 + Vs2 \ldots..Vs(n)] \text{ .... (2.12)}$$

2.3 Servo Valve [5]

Servo valve hidrolik adalah *valve* yang berfungsi untuk mengatur oli yang akan masuk pada ruang hidrolik dan digunakan untuk mengendalikan arah dan besar pergerakan dari aktuator hidrolik suatu peralatan. Sistem hidrolik memiliki karakteristik, gaya yang kecil dapat digunakan untuk menggerakkan atau mengangkat beban berat dengan cara mengubah perbandingan luas penampang silinder.

Servo valve adalah katup kontrol arah dengan spool/jarum, dengan mekanisme yang digerakkan menggunakamn arus yang menggerakkan motor torsi untuk mengontrol posisi spool/jarum. Motor torsi dapat dianggap sebagai *transduser* elektromekanik yang menghasilkan defleksi kecil sebanding dengan arus input. Ini dapat memberikan gerakan yang diperlukan ke kumparan baik secara langsung maupun tidak langsung. Kumparan dapat diposisikan tak terbatas untuk mengendalikan arah aliran dan jumlah tekanan, sebagai respons terhadap sinyal kontrol listrik / elektronik. servo valve tersedia dalam desain satu tahap, dua tahap, atau tiga tahap. Katup servo satu-tahap terdiri dari motor torsi yang langsung melekat pada kumparan geser katup.

Motor torsi harus menyediakan torsi yang cukup ke katup untuk menggeser kumparannya secara langsung melawan tekanan yang berlawanan. Valve satu tahap memiliki kemampuan daya terbatas. *Servo Valve* dua-tahap terdiri dari motor torsi, spul pilot, dan spul utama. Pertama, motor torsi menggeser spul pilot, yang pada gilirannya, mengarahkan aliran fluida untuk memindahkan spul utama. Didalam *Servo Valve* tiga-tahap, tahap pilot dibagi menjadi dua, yaitu pilot tahap pertama, dan pilot tahap ke-2. Spool percontohan tahap pertama menggeser spul pilot tahap kedua, yang, pada gilirannya, menggeser spul utama. *Servo Valve* tiga-tahap digunakan untuk aplikasi dengan kebutuhan aliran tinggi, tekanan tinggi



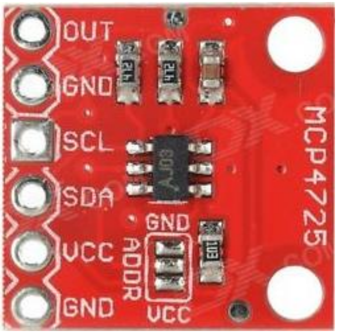
Gambar 2.5 Gambar *torque motor* dan rangkaian dalam *servo valve*

Servo valve hidrolik terdiri atas sistem kontrol loop tertutup yang terdiri dari sistem pengaturan posisi, pengaturan kecepatan, pengaturan aliran, dan jarum *servo*. Komputer sebagai memberi nilai set point akan memberi perintah kepada *mikrokontroller*, mikrokontroller yang mengeluarkan sinyal digital. Sinyal digital yang dihasilkan, diberi rangkaian pengondisi sinyal (*signal conditioning*) guna memberi sinyal perintah ke *servo amplifier*.

2.5 Modul *Digital to Analog Converter MCP4725 (DAC)* [6]

DAC adalah perangkat yang digunakan untuk mengkonversi sinyal masukan dalam bentuk digital menjadi sinyal keluaran dalam bentuk analog (tegangan). Tegangan keluaran yang dihasilkan DAC sebanding dengan nilai digital yang masuk ke dalam DAC.Sebuah DAC menerima informasi digital dan mentransformasikannya ke dalam bentuk suatu tegangan analog. Informasi digital adalah dalam bentuk angka biner dengan jumlah digit yang pasti. Konverter D/A dapat mengonversi sebuah angka digital ke dalam sebuah tegangan analog dengan memberikan skala keluaran analog bernilai nol ketika semua *bit* adalah nol dan sejumlah nilai maksimum ketika semua *bit* adalah satu. Angka *biner* sebagai angka pecahan.

Aplikasi DAC banyak digunakan sebagai rangkaian pengendali (*driver*) yang membutuhkan masukan analog seperti motor AC maupun DC, tingkat kecerahan pada lampu, pemanas *(Heater)* dan sebagainya. Umumnya DAC digunakan untuk mengendalikan peralatan komputer. Untuk aplikasi modern hampir semua DAC berupa rangkaian terintegrasi (IC), yang diperlihatkan sebagai kotak hitam memiliki karakteristik masukan dan keluaran tertentu.



Gambar 2.6 Gambar Modul *DAC MCP4725*

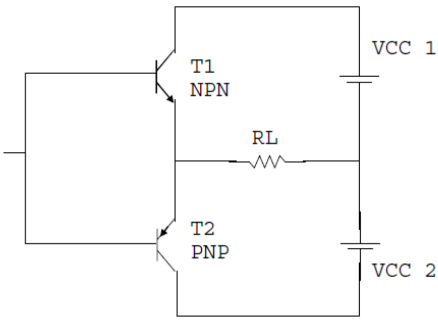
SDA adalah pin serial data dari interface I2C. pin SDA digunakan untuk menulis atau membaca register DAC dan data EEPROM. pin SDA adalah sebuah open-drain N-chanel driver. oleh karena itu, dibutuhkan sebuah pull-up resistor dari jalur VDD ke pin SDA. kecuali untuk kondisi start dan stop. data di pin SDA harus stabil selama clock dalam keadaan HIGH. keadaan HIGH atau LOW dari pin SDA hanya dapat berubah ketika sinyal clock di pin SCL bernilai LOW.

SCL adalah pin serial clock pada interface I2C. MCP4725 hanya bertindak sebagai slave dan pin SCL hanya menerima serial clock dari luar. data input dari master device digeser ke pin SDA di rising edges pada SCL *clock* dan keluaran dari MCP4725 terjadi saat falling edges pada SCL *clock*. pin SCL adalah sebuah open-drain N-chanel driver. oleh karena itu, dibutuhkan pull-up resistor dari jalur VDD ke pin SCL.

2.6 Rangkaian Penguat *Push-Pull* komplementer [7]

Penguat daya komplementer merupakan bentuk lain penguat push pull yang menggunakan dua buah transistor PNP dan NPN yang saling berkomplementer. Keuntungan penguat komplementer adalah tidak diperlukan adanya trafo input dan trafo output.

Meskipun tanpa trafo untuk pembelah dasa pada input penguat komplementer, maka dengan adanya transistor 1 dan transistor 2 yang berbeda jenisnya dengan sendirinya menghantarkan (atau mati) secara bergantian. Pada saat siklus input positif, maka basis-emitor transistor 1 mendapat bias maju sehingga transistor 1 (T1) hidup sedangkan basis emmiter Transistor 2 (T2) mendapat bias mundur (PNP). Pada saat sinyal input berubah menjadi negatif, maka basis-emitor T1 mendapat bias mundur (reverse bias) sehingga T1 mati, sedangkan basis-emittor T2 mendapat bias maju (Forward bias) (PNP) sehingga T2 menjadi hidup



Gambar 2.7 Gambar rangkaian push pull komplementer

Konfigurasi dasar tiap penguat transistor dalam penguat simetri komplementer adalah pengikut emitor, karena sinyal output diambil dari kaki emittor.

2.2 STM32F103C [8]

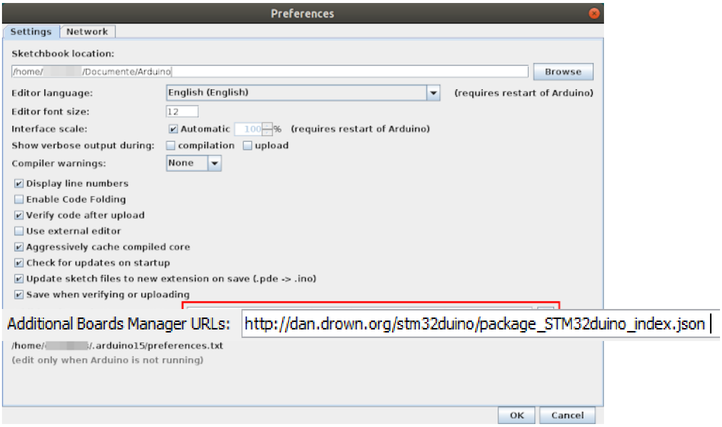
"*Blue Pill*" adalah sebuah papan pengembangan berbasis STM32F103. STM32F103 adalah sebuah alat dengan *Cortex-M3 ARM CPU* yang berkecepatan 72MHz, mempunyai *RAM 20 Kb* dan mempunyai flash memori sebesar 64 atau 128 Kb. *Mikrokontroler* nya mempunyai *port USB*, dua *port serial*, *pin PWM 16 bit*, dan *pin ADC 12 bit*. STM32F103 bekerja pada tegangan 3,3 *V* tetapi beberapa mempunyai pin toleransi 5*V*.

Pemrograman pada *board* ini dapat dipermudah yaitu dengan menggunakan *software Arduino IDE*. Tetapi sebelum itu, sebuah *bootloader Arduino* harus di *flash* kedalam *board* STM32F103. Ini bisa dilakukan melalui *port serial* atau menggunakan *interface debug* pada *MCU* dengan *ST-Link tool*.

Gambar 2.8 Gambar STM32F103C

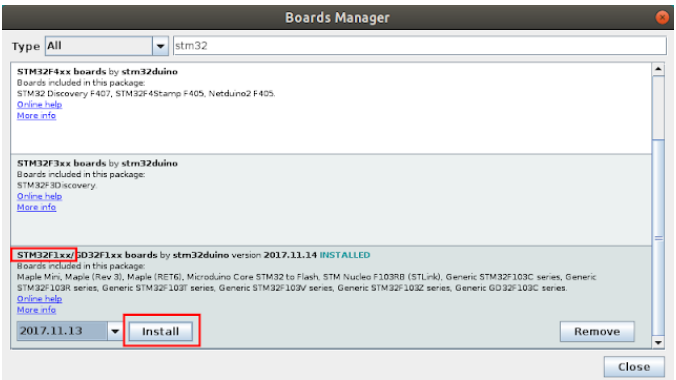
Arduino IDE tidak hadir dengan dukungan *default* untuk papan STM32F103. Oleh karena itu harus di *setting* terlebih dahulu agar papan STM32F103 bisa dientegrasikan dengan *Arduino IDE*. Berikut *step* untuk semua sistem operasi :

Jalankan *Arduino IDE*, pilih *File – Preferences*, dan tambahkan *URL* ini pada *board manager* yang tersedia “ ***http://dan.drown.org/stm32duino/package_STM32duino_index.json*** “ klik *OK* untuk menutup dialog. Dapat dilihat pada gambar 2.6.



Gambar 2.9 Memasukkan *URL* untuk *flash* STM32F103

Setelah itu, pilih *Tools – Board Manager*. Didalam dialog yang muncul, cari *STM32* dan pilih *STM32F1XX* untuk “*Blue Pill*”. Jika *board* menggunakan *chipset* yang berbeda (contoh : STM32F3) pilih seperti yang tertera pada *board* lalu *install*. Untuk *step* nya bisa dilihat pada gambar 2.7.



Gambar 2.10 Meng*instal board* STM32F103 ke *Arduino IDE*

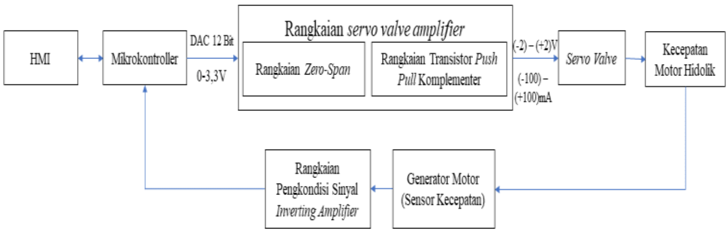
Sebelum benar – benar mengunggah *sketches* ke dalam *board*, dibutuhkan *bootloader STM32duino*. Disini menggunakan sebuah *ST – Link V2 clone* untuk memasukkan *bootloader* nya. Koneksi ke *board* STM32F103 sangat mudah, menggunakan *SWCLK, SWDIO, GND* dan *pin 3,3V*. sambungkan semua menggunakan kabel *jumper* yang sudah tersedia pada *ST – Link clone*. Pindahkan *jumper* untuk *set BOOT0 to 1*.

BAB III
PERENCANAAN DAN PEMBUATAN ALAT

Pada bab ini berisi tahapan mengenai tahapan yang dilakukan dalam perencanaan dan pembuatan Tugas Akhir. Penjelasan diawali dengan blok fungsional sistem secara keseluruhan yang meliputi proses kerja alat dalam bentuk alur diagram dan perancangan pada rangkaian yang digunakan.

3.1 Blok Fungsional Sistem

Dalam sebuah perancangan, diperlukan blok fungsional sistem berupa blok diagram yang menjelaskan sistem kerja secara keseluruhan Tugas Akhir "**Perancangan dan Penerapan Driver *Servo Valve* pada Modul *Elektro Hidrolik Servomechanism* (EHS 160)**". Secara keseluruhan blok fungsional sistem dapat dilihat pada Gambar 3.1.



Gambar 3.1. Gambar Blok Diagram Sistem kontrol modul hidrolik

Pada diagram blok gambar 3.1 menjelaskan bahwa perancangan untuk membuat driver *servo valve* ini terdapat beberapa tahap yaitu dari *mikrokontroller* mengirimkan perintah pada modul DAC, *mikrokontrolle*r menggunakan jenis STM32F4103C. Kemudian dari modul DAC yang menerima perintah sinyal dari *mikrokontroller* ini mengeluarkan tegangan keluaran sesuai dengan perintah dari *mikrokontroller*, tegangan keluaran yang dihasilkan dari DAC kemudian diolah kembali dengan rangkaian *zero-span*, rangkaian *zero-span* akan mengolah kembali menjadi tegangan sesuai yang dibutuhkan *servo valve* yaitu tegangan positif (+) dan tegangan negatif (-). Karena *servo valve* ini dikendalikan menggunakan arus.

Maka digunakan rangkaian *push pull* komplemen. *Output* dari rangkaian *push pull* komplemen disambungkan pada kabel servo valve. *voltage* dari *servo valve* digunakan untuk mengatur buka tutup *servo valve* yang akan mengatur kecepatan putar dari piringan. Putaran piringan tersebut di baca oleh sensor *tachometer* yang berupa motor DC lalu data tersebut dimasukkan kembali menuju *mikrokontroler* melalui program ADC

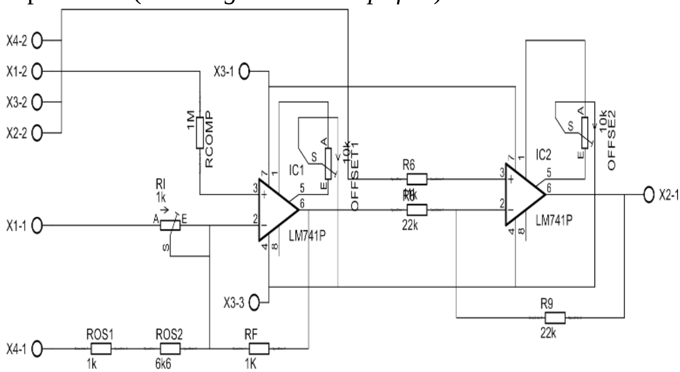
3.2 Perancangan *Hardware*

Hardware yang akan dibuat adalah berupa rangkaian – rangkaian yang digunakan untuk mengoptimalkan kinerja system dalam Tugas Akhir yaitu meliputi:

1. Rangkaian *Zero-Span*
2. Rangkaian *push pull* komplemen
3. Rangkaian inverting ampilfier

3.2.1 Rangkaian *Zero-Span*

Rangkaian *Zero span* adalah rangkaian yang dapat memungkinkan untuk menghasilkan parameter yang sesuai untuk tegangan yang diinginkan. Rangkaian pengubah *span dan zero* dapat dibuat dengan menggunakan rangkaian penjumlah dan pembalik (*inverting summer amplifier*).



Gambar 3.2 Gambar skematik rangkaian *zero-span*

Rangkaian *Zero-Span* yang dirancang seperti pada gambar 3.2 *Output* sesuai sementara pada *mikrokontroller* adalah hanya sebesar 0V - 3.3V sedangkan pada *servo* dibutuhkan tegangan amplifier sebesar (-2)V – (+2)V. Pada rangkaian *Zero-Span* yang dirancang, pengaturan tegangan *output* dapat diatur melalui Ri yang ada pada rangkaian *zero-span* dengan Rf yang ditentukan, dan Ros adalah mengatur tegangan penguat zero offset pada rangkaian tersebut. Untuk mengeluarkan tegangan output sebesar (-2) V – (+2) V dan tegangan input 0V – 3,3V, maka digunakan rumus perancangan sebagai berikut :

menentukan nilai gradien

$$m = \frac{Vout \max - Vout \min}{Vin \max - Vout \min} \quad \text{.................. (3.1)}$$

$$= \frac{2-(-2)}{3{,}3-0}$$

$$= 1{,}2121$$

menentukan nilai resistor Rf, Ri, Ros, dan Rcomp

Rf diberi nilai 1KΩ

Dan menentukan nilai Ri menggunakan rumus

$$Ri = \frac{Rf}{m} \quad \text{.. (3.2)}$$

$$= \frac{1k\Omega}{1{,}2121}$$

$$= 825{,}0124\ \Omega$$

Maka Ri menggunakan potensiometer jenis multiturn 1KΩ, yang kemudian diatur nilainya menjadi 825,0124 Ω

Menentukan nilai b

$$b = Vout \min - m * Vin \min \quad \text{.............. (3.3)}$$

$$b = (-2) - (1{,}2121 * (0))$$

$$b = -2$$

Untuk mencari Ros dan menetapkan Vreff -15 V

$$Ros = \frac{Rf * Vreff}{-2} \quad \text{................................(3.4)}$$

$$= \frac{1K\Omega * (-15)}{-2}$$

$$= 7500\ \Omega$$

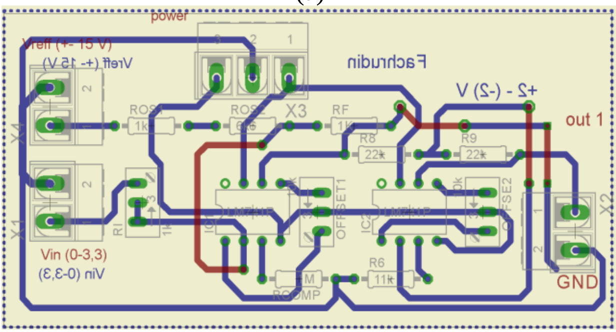
Nilai resistor Rcomp merupakan nilai pararel Rf, Ri, dan Ros

$$Rcomp = Rf//Ri//Ros \quad \text{..............................(3.5)}$$

$$Rcomp = 663.556{,}192\Omega$$

Pengujian dan data percobaan rangkaian *zero span* dapat dilihat pada bab 4 tabel 4.2 pada sub bab 4.1

(a)

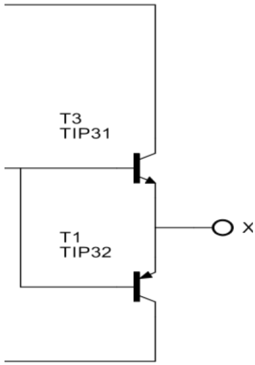


(b)

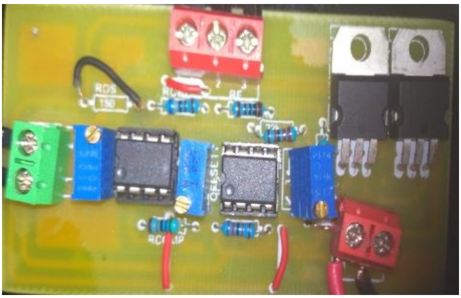
Gambar 3.3 Gambar rangkaian *zero-span* (a) dan rangkaian wiring *zero span* (b)

3.2.2 Rangkaian *Push Pull* komplementer

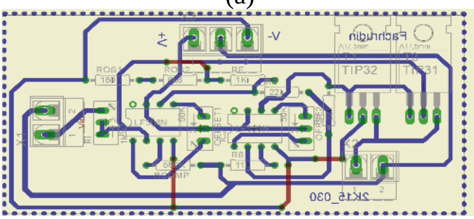
Rangkaian push pull pada tahap perancangan ini digunakan sebagai penguat daya dan arus untuk mengendalikan servo valve, dengan mengendalikan arus dari -100mA - 100mA pada vcc ±15V yang kemudian basis dari transistor diberi input ±2V dari rangkaian zero span dan mikrokontroller untuk mengatur kebutuhan arus pada servo valve. Transistor yang digunakan disini adalah transistor TIP 31 (NPN) dan TIP 32 (PNP). Pada saat siklus input positif, maka basis-emitor transistor 1 mendapat bias maju sehingga transistor 1 (TIP31) hidup sedangkan basis emmiter Transistor 2 (TIP32) mendapat bias mundur (PNP). Pada saat sinyal input berubah menjadi negatif, maka basis-emitor T1 mendapat bias mundur (reverse bias) sehingga T1 mati, sedangkan basis-emittor T2 mendapat bias maju (Forward bias) (PNP) sehingga Transistor 2 menjadi hidup. Rangkaian skematik dapat dilihat pada gambar 3.4, pada gambar 3.5 adalah rangkaian perancangan yang telah diintegrasikan dengan rangkaian *zero-span*. Hasil dari pengujian yang diperoleh dari rangkaian push pull kompemen ini ada pada tabel 4.9



Gambar 3.4 Gambar skematik rangkaian *Push Pull* komplementer



(a)

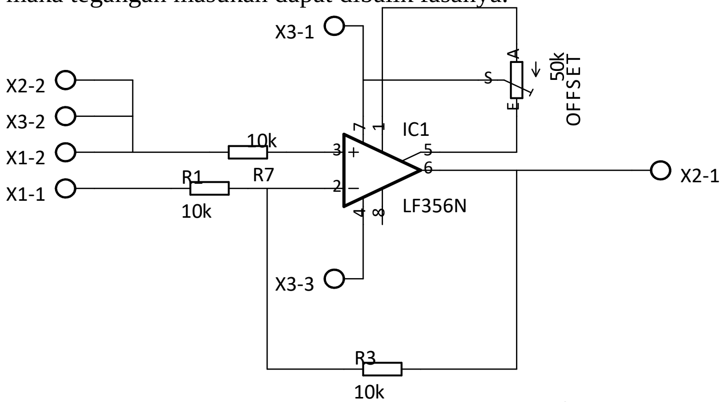


(b)

Gambar 3.5 Gambar zero-span yang telah terintegrasi dengan rangkaian push pull komplenter (a) dan rangkaian wiring pada zero-span dan pushpul komplementer (b)

3.2.3 Rangkaian *Inverting Amplifier*

Rangkaian penguat inverting amplifier adalah penguat yang digunakan sebagai pembalik dan rangkaian pengkondisi sinyal sensor, karena sensor yang berupa motor DC dapat bernilai negatif, maka diperlukan rangkaian inverting amplifer sebagai pengkondisi sinyal agar terbaca pada mikrokontroller. Dari table 4. yang menunjukkan keluaran tegangan dari kecepatan sensor motor dc ini. Rangkaian inverting yang dirancang dapat dilihat pada gambar 3.6, dengan penguatan 1x, maka tegangan masukan dapat dibalik fasanya.



Gambar 3.6 Gambar skematik rangkaian *Inverting Amplifier*

3.2.4 Rangkaian integrasi perangkat *driver servo valve*

Rangkaian hardware dari driver servo valve terdiri atas rangkaian zero-span dan rangkaian push pull komplementer. Dari hasil tabel 4.7 pada sub bab 4.3 dapat dilihat bahwa tegangan output yang dihasilkan ketika diberi beban ada ketidak sesuaian rpm putar kanan dan putar kiri, putar kanan cenderung lebih sedikit dan lambat dibanding putar kiri, selain itu arus yang dihasilkan kurang memenuhi kebutuhan dari servo untuk menggerakkan motor hidrolik. Maka dari itu perancangan driver servo valve dirancang kembali dengan asumsi awal tegangan keluaran dari keluaran zero-span menjadi (-2,2)V hingga (2,6)V. berikut merupakan perhitungan perancangan terhadap rancangan zero span :

$$m = \frac{Vout\ \max - Vout\ \min}{Vin\ \max - Vout\ \min} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3.6)$$

$$= \frac{2{,}6-(-2{,}2)}{3{,}3-0}$$

$$= 1{,}4545456$$

menentukan nilai resistor Rf, Ri, Ros, dan Rcomp

Rf diberi nilai 1KΩ

Dan menentukan nilai Ri menggunakan rumus

$$Ri = \frac{Rf}{m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3.7)$$

$$= \frac{1k\Omega}{1{,}4545456}$$

= 687,4998 **Ω**

Maka Ri menggunakan potensiometer jenis multiturn 1K**Ω**, yang kemudian diatur nilainya menjadi 687,4998 **Ω**

Menentukan nilai b

$$b = Vout\ \text{min} - m * Vin\ \text{min} \ldots\ldots..\ldots(3.8)$$

$$b = (-2{,}2) - 1{,}2121 * (0)$$

$$b = -2{,}2$$

Untuk mencari Ros dan menetapkan Vreff -15 V

$$Ros = \frac{Rf*Vreff}{-2{,}2} \ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots..(3.9)$$

$$= \frac{1K\Omega*(-15)}{-2{,}2}$$

= 6880,728 **Ω**

Maka Ros dipilih resistor dengan nilai 6k8

Nilai resistor Rcomp merupakan nilai jumlah pararel Rf, Ri, dan Ros

$$Rcomp = Rf//Ri//Ros \ldots\ldots\ldots\ldots\ldots\ldots(\ldots\ldots3.10)$$

$$Rcomp = 557.190{,}503\Omega$$

Rcomp dipilih menggunakan nilai resistansi 560K**Ω**.

Hasil dari perancangan ke 2 zero-span dan rangkaian push-pull komplementer dapat dilihat pada tabel 4.9

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BAB IV
PENGUJIAN DAN ANALISA DATA

Pengujian dan analisa data ini dilakukan untuk mengetahui perancangan dan pembuatan telah tercapcai atau belum dan melakukan proses evaluasi atas perancangan dan pembuatan alat. Pengujian sistem yang dilakukan merupakan pengujian terhadap perangkat keras dan perangkat lunak dari sistem secara keseluruhan yang telah selesai untuk memastikan sistem yang akan digunakan dapat berfungsi dengan baik sehingga akan bekerja secara optimal

4.1 Pengukuran Tegangan Keluaran Rangkaian *Zero-Span*

Pengukuran pertama merupakan pengukuran pada rangkaian *zero-span*. Pengukuran ini dilakukan dengan cara mengukur tegangan pada tegangan keluaran yang diinginkan yaitu sebesar (-2) V – (+2) V. Dengan ketentuan resistor pada tabel 4.1 :

Tabel. 4.1 Resistor Rangkaian *Zero-Span*

Rf	1kΩ
Ri	825Ω
Ros	7500Ω
Rcomp	680kΩ

Berikut merupakan hasil dari rangkaian *Zero-span* dengan *input* tegangan dari *power supply* dan *op-amp* menggunakan ic LF356:

Tabel. 4.2 Pengukuran Rangkaian *Zero-Span*

No	Vin	Vout	A
1	0	-1,92	*div*
2	0,12	-1,831	-15,258
3	0,2	-1,699	-8,495
4	0,33	-1,548	-4,6909
5	0,52	-1,335	-2,5673
6	0,73	-1,095	-1,5
7	0,97	-0,816	-0,8412
8	1,09	-0,657	-0,6028
9	1,24	-0,49	-0,3952

10	1,45	-0,255	-0,1759
11	1,67	0	0
12	1,88	0,205	0,10904
13	2,06	0,38	0,18447
14	2,2	0,64	0,29091
15	2,4	0,9	0,375
16	2,52	0,99	0,39286
17	2,6	1,11	0,42692
18	2,8	1,301	0,46464
19	2,9	1,46	0,50345
20	3,01	1,562	0,51894
21	3,22	1,804	0,56025
22	3,31	1,917	0,57915

Pengukuran kedua pada pengukuran rangkaian *zero-span* dengan menggunakan Vin disambungkan dengan modul DAC.

Tabel. 4.3 Hasil pengukuran Vout DAC dengan rangkaian Vout *Zero-span*

No	**Nilai Diskrit**	**Vout DAC**	**Vout *Zero-span* (V)**
1	1	1,1 mv	-1,917
2	2	1,9 mv	-1,917
3	3	2,8 mv	-1,917
4	4	3,7 mv	-1,917
5	5	4,5 mv	-1,916
6	6	5,4 mv	-1,916
7	7	6,3 mv	-1,916
8	8	7,2 mv	-1,916
9	9	8,0 mv	-1,916
10	10	8,9 mv	-1,916
11	50	43,7 mv	-1,915
12	100	86,6 mv	-1,915
13	500	0,41 v	-1,547
14	1000	0,81 v	-1,124
15	2000	1,63 v	-0,195
16	3000	2,44 v	0.858
17	4000	3,25 v	1,857

18	4095	3,3 v	1,917

Dengan data yang diperoleh kemudian dibandingkan dengan teori yang ada dengan menggunakan rumus Vout rangkaian *zero-span* persamaan 2.7 yang ada pada bab 2 yang dapat dilihat dihalaman. Maka diperoleh data perhitungan sebagai berikut :

Tabel 4.4 Tabel Pengukuran dengan menggunakan rumus *Zero-span*

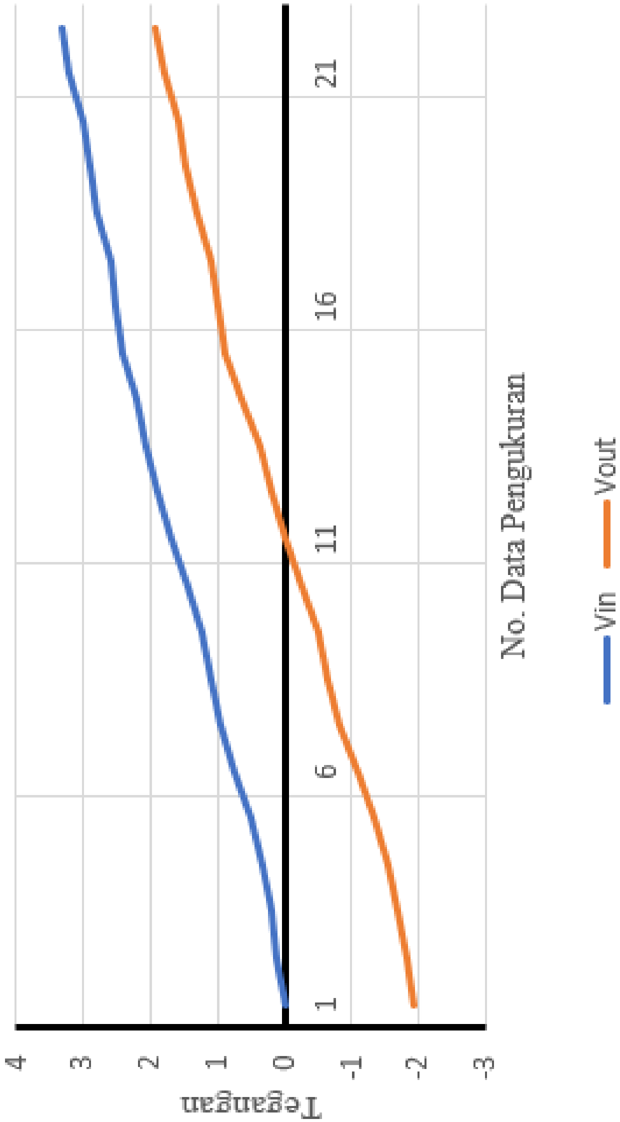
No	Vin	Rf	Ri	Ros	Rcomp	Vout
1	0	1000	825	7500	663556	-2
2	0,12	1000	825	7500	663556	-1,8545455
3	0,2	1000	825	7500	663556	-1,7575758
4	0,33	1000	825	7500	663556	-1,6
5	0,52	1000	825	7500	663556	-1,369697
6	0,73	1000	825	7500	663556	-1,1151515
7	0,97	1000	825	7500	663556	-0,8242424
8	1,09	1000	825	7500	663556	-0,6787879
9	1,24	1000	825	7500	663556	-0,4969697
10	1,45	1000	825	7500	663556	-0,2424242
11	1,67	1000	825	7500	663556	0,0242424
12	1,88	1000	825	7500	663556	0,2787879
13	2,06	1000	825	7500	663556	0,4969697
14	2,2	1000	825	7500	663556	0,6666667
15	2,4	1000	825	7500	663556	0,9090909
16	2,52	1000	825	7500	663556	1,0545455
17	2,6	1000	825	7500	663556	1,1515152
18	2,8	1000	825	7500	663556	1,3939394
19	2,9	1000	825	7500	663556	1,5151515
20	3,01	1000	825	7500	663556	1,6484848
21	3,22	1000	825	7500	663556	1,9030303
22	3,31	1000	825	7500	663556	2,013225

Dengan perbandingan nilai yang didapat melalui pengukuran dengan menggunakan rangkaian hardware dan secara rumus, maka dibandingkan data yang diperoleh. Hasil perbandingan secara perhitungan matematik teori dengan secara rangkaian zero-span yang telah dibuat dapat dilihat pada tabel 4.4 sebagai berikut :

Tabel 4.5 Tabel perbandingan secara teori dan secara rangkaian langsung

No	Vin (V)	Vout secara teori (V)	Vout pada rangkaian (V)	Selisih (V)
1	0	-2	-1,92	-0,081
2	0,12	-1,8545455	-1,831	-0,0235455
3	0,2	-1,7575758	-1,699	-0,0585758
4	0,33	-1,6	-1,548	-0,052
5	0,52	-1,369697	-1,335	-0,034697
6	0,73	-1,1151515	-1,095	-0,0201515
7	0,97	-0,8242424	-0,816	-0,0082424
8	1,09	-0,6787879	-0,657	-0,0217879
9	1,24	-0,4969697	-0,49	-0,0069697
10	1,45	-0,2424242	-0,255	0,0125758
11	1,67	0,0242424	0	0,0242424
12	1,88	0,2787879	0,205	0,0737879
13	2,06	0,4969697	0,38	0,1169697
14	2,2	0,6666667	0,64	0,0266667
15	2,4	0,9090909	0,9	0,0090909
16	2,52	1,0545455	0,99	0,0645455
17	2,6	1,1515152	1,11	0,0415152
18	2,8	1,3939394	1,301	0,0929394
19	2,9	1,5151515	1,46	0,0551515
20	3,01	1,6484848	1,562	0,0864848
21	3,22	1,9030303	1,804	0,0990303
22	3,31	2,01	1,917	0,0951212

Dengan demikian, terdapat eror atau selisih dari hasil perhitungan secara teori dengan hasil pengukuran pada rangkaian yang telah dibuat yaitu 0,081V – 0,095V, namun tidak berpengaruh signifikan pada sistem driver, selisih hasil tabel diatas dikarenakan tidak adanya nilai yang sesuai nilai resistor yang ditemukan selain itu nilai setiap komponen memiliki nilai toleransi masing-masing. Dari perancangan ini, hasilnya sudah hampir memenuhi kriteria perancangan yaitu tegangan masukan sebesar 0 V – 3,3 V dengan tegangan keluaran sebesar (-2) V – (+2)V. Gambar grafik perbandingan vout dengan vin zero sapan dapat dilihat pada gambar 4.1



Gambar 4.1 Gambar grafik Vin dan Vout Rangkaian Zero-Span pada tabel 4.2

4.2 Pengukuran Rangkaian *Push Pull* Komplementer

Pengukuran selanjutnya adalah pengukuran pada rangkaian *Push Pull* Komplementer. Pengukuran ini dilakukan dengan cara mengukur arus pada beban (*load*), dengan mengetahui arus beban maka akan dapat menghitung arus yang mengalir pada beban. Beban yang dipilih adalah mendekati beban resistansi servo valve sebesar 33 ohm. Berikut adalah hasil dari pengukuran *Push Pull Komplementer*

Tabel 4.6 Tabel Pengukuran Rangkaian *Push Pull Komplementer*

No	Vin DAC	Vout Zero-span	Hasil pengujian Arus
1	0	-1,973	-36,3939
2	0,12	-1,83	-34,0606
3	0,2	-1,698	-31,8182
4	0,33	-1,508	-25,4848
5	0,52	-1,32	-23,3939
6	0,73	-1,078	-18,7879
7	0,97	-0,821	-15,5152
8	1,09	-0,74	-11,8182
9	1,24	-0,419	-7,87879
10	1,45	-0,194	-3,48485
11	1,73	0,278	0,090909
12	1,88	0,617	3,939394
13	2,06	1,1	8,181818
14	2,2	1,202	13,48485
15	2,4	1,41	16,24242
16	2,52	1,671	19,78788
17	2,6	1,712	24
18	2,8	1,87	29,09091
19	2,9	1,95	33,0303

20	3,01	2	36,06061
21	3,22	-2,17	36,87879
22	3,3	-2,23	38,9697

Dilihat pada tabel 4.4 yang dihasilkan dari pengukuran rangkaian *Push Pull* Komplementer, menunjukkan hasil yang jauh dari arus yang diinginkan. Ini merupakan pengaruh digunakannya resistor 33 Ω yang hanya berdaya ¼ watt dan rangkaian *push-pull* komplementer ini mengatur arus dari *input* kaki basis transistor

4.3 Pengukuran Rangkaian integrasi perangkat *driver servo valve* (bagian 1)

Pengujian rangkaian yang dimaksud disini adalah rangkaian zero-span dan rangkaian push-pull komplementer yang digunakan untuk mengendalikan aliran oli pada servo valve dan mengendalikan gerakan motor hidrolik. Tabel 4.6 merupakan hasil pengujian rangkaian driver servo valve dengan menggunakan *input* 0-3,3 V dari mikrokontroller dan modul DAC dan outputnya mengendalikan buka tutup servo valve.

Tabel 4.7 Tabel susunan resistor untuk *zero-span* perancangan *driver servo valve* bagian 1

Rf	1kΩ
Ri	825Ω
Ros	7500Ω
Rcomp	680kΩ

Tabel 4.8 Tabel hasil pengukuran rangkaian *driver servo valve* terhadap beban *servo valve.*

No	Vin (V)	Vout Zero-Span (V)	Vout setelah push pull (V)	Iout (mA)
1	0	-1,919	-1,26	-28,96
2	0,12	-1,831	-1,181	-28,12
3	0,2	-1,699	-1,05	-27,35

4	0,33	-1,548	-0,92	-23,19
5	0,52	-1,335	-0,711	-16,92
6	0,73	-1,095	-0,421	-9,73
7	0,97	-0,816	-0,189	-2,59
8	1,09	-0,657	-0,036	-1,21
9	1,24	-0,49	-0,018	-0,62
10	1,45	-0,255	-0,002	-0,04
11	1,67	0	0,006	0
12	1,88	0,205	0,029	0,09
13	2,06	0,38	0,72	0,47
14	2,2	0,64	0,172	1,51
15	2,4	0,9	0,242	2,47
16	2,52	0,99	0,354	4,82
17	2,6	1,11	0,458	8,21
18	2,8	1,301	0,651	11,36
19	2,9	1,46	0,817	15,81
20	3,01	1,562	0,91	19,74
21	3,22	1,804	1,126	23,95
22	3,31	1,917	1,173	28,27

Dari data diatas diperoleh pada tabel 4.8, menunjukkan hasil integrasi rangkaian perangkat driver servo valve masih jauh dari yang diinginkan untuk mengatur pergerakkan motor hidrolik. Untuk itu dilakukan perancangan integrasi perangkat driver servo valve bagian kedua yang dapat dilihat pada sub bab 4.4

4.4 Pengukuran Rangkaian integrasi perangkat *driver servo valve* (bagian 2)

Dilihat dari pengujian rangkaian pada sub bab 4 Pengujian rangkaian yang dimaksud disini adalah rangkaian zero-span dan rangkaian push-pull komplementer dengan output dari rangkaian zero-span yang digunakan untuk mengendalikan aliran oli pada servo valve dan mengendalikan gerakan motor hidrolik. Karena kebutuhan arus terhadap gerak servo valve yang kurang dari kebutuhan. Maka perancangan kedua dari driver servo valve ini dilakukan kembali guna menguatkan arus pada servo valve

Tabel 4.9 Tabel susunan resistor untuk *zero-span* perancangan *driver servo valve* bagian 1

Rf	1kΩ
Ri	687,499Ω
Ros	6800Ω
Rcomp	560kΩ

Tabel 4.10 Tabel hasil pengukuran rangkaian *driver servo valve* terhadap beban *servo valve* dari perancangan ke 2.

Vin (V)	Vout zero-span (V)	Vout setelah rangkaian push pull (V)	Arus (mA)
0	-1,973	-1,84	-84,2
0,12	-1,83	-1,665	-73,2
0,2	-1,698	-1,57	-66
0,33	-1,508	-1,403	-59,12
0,52	-1,32	-1,224	-40,85
0,73	-1,078	-1,019	-38,69
0,97	-0,821	-0,762	-32,5
1,09	-0,74	-0,677	-25,42
1,24	-0,419	-0,348	-16,91
1,45	-0,194	-0,119	-9,38
1,73	0,278	0,219	2,52
1,88	0,617	0,55	8,128
2,06	1,1	1,021	16,75
2,2	1,202	1,129	24,19
2,4	1,41	1,337	31,74
2,52	1,671	1,6	39,04
2,6	1,712	1,63	45,24
2,8	1,87	1,806	52,97

2,9	1,95	1,88	60,81
3,01	2	1,91	67,93
3,22	-2,17	2,006	72,48
3,3	-2,23	2,03	80,67

Dari data diatas diperoleh pada tabel 4.9, menunjukkan hasil integrasi rangkaian perangkat driver servo valve hamper mendekati arus yang diinginkan untuk mengatur pergerakkan motor hidrolik melalui servo valve. Perancangan untuk driver servo valve dapat menggunakan perancangan pada bagian kedua ini.

4.5 Pengukuran Tegangan Generator DC Sebagai Sensor Kecepatan

Pengujian ini ditujukan untuk membandingkan data sensor kecepatan menggunakan alat ukur tachometer digital dengan tegangan yang dihasilkan sensor kecepatan berupa generator DC agar mendapatkan hasil yang diinginkan. Pada tabel 4.10 adalah hasil pengukuran terhadap keluaran dari generator DC sebagai sensor kecepatan. Hasil ini nantinya akan dijadikan sebagai pengambilan data yang akan masuk pada HMI.

Tabel 4.11 Tabel hasil pengukuran keluaran generator dc sebagai sensor kecepatan

Vout Sensor putaran berupa generator dc (V)	Kecepatan (RPM)	Arah Putar
3,55	175	Kiri
3,51	170	Kiri
2,1	100	Kiri
0,299	78	Kiri
1,075	55	Kiri
0,91	48	Kiri
0,915	48	Kiri

0,7	10,4	Kiri
0,65	34	Kiri
0,4	10,4	Kiri
0	0	Tidak berputar
-0,33	26	Kanan
-0,9	49,7	Kanan
-1,02	57,9	Kanan
-1,82	90,2	Kanan
-2,087	102,5	Kanan
-2,43	139,2	Kanan
-2,78	156,2	Kanan
-3,17	175,2	Kanan
-3,24	182	Kanan
-3,44	195	Kanan
-3,45	197	Kanan
-3,521	201	Kanan
-3,521	201	Kanan

Dari data yang dihasilkan pada tabel 4.10 dapat diketahui bahwa ketika sensor kecepatan yang berupa generator DC ini berputar kearah kanan, maka tegangan akan bernilai negative, sedangkan ketika berputar kearah kiri, maka tegangan akan bernilai positif. Dari tabel 4.10 juga ditunjukkan nilai maksimum kecepatan putaran motor hidrolik pada saat berputar kearah kanan adalah 201 Rpm pada tegangan keluaran generator DC -3,521 V sedangkan nilai maksimum kecepatan putaran motor hidrolik pada saat berputar kearah kiri adalah 175 Rpm pada tegangan keluaran generator DC +3,551V. nilai minimum atau pada saat keadaan berhenti kecepatan pada kedua arah tersebut adalah 0V

4.6 Pengukuran Tegangan Masukan Terhadap Kecepatan Generator

Pengujian ini ditujukan untuk mengetahui tegangan *input* dari mikrokontroller terhadap kecepatan generator DC sebagai sensor kecepatan. Tabel 4.11 merupakan tabel pengukuran tegangan mikrokontroller yang disambungkan dengan modul DAC dan keluaran tegangan sensor keceptan Hasil ini nantinya akan dijadikan sebagai pengambilan data yang akan masuk dan diproses pada HMI. HMI akan mengambil data kecepatan motor hidrolik dari generator DC.

Tabel 4.12 Tabel hasil pengukuran tegangan *input* dac dari mikrokontroller dan tegagan *output* dari sensor putaran generator DC

Vout DAC (V)	Vout Zero-span dan Push Pull Komplementer (V)	Vout Sensor putaran generator DC (V)
0	-1,68	3,55
0,02	-1,578	3,51
0,67	-0,557	2,1
0,88	-0,313	0,299
1	-0,275	1,075
1,2	-0,1	0,91
1,5	-0,0091	0,915
1,6	-0,0073	0,7
1,7	-0,0051	0,65
1,8	0,0021	0,4
1,948	0	0
2,1	0,655	-0,33
2,2	0,805	-0,9
2,3	0,809	-1,02
2,4	1,12	-1,82
2,5	1,28	-2,087
2,6	1,44	-2,43
2,7	1,59	-2,78
2,8	1,746	-3,17
2,9	1,89	-3,24

3,05	1,98	-3,44
3,1	2,08	-3,45
3,19	2,18	-3,521
3,3	2,18	-3,521

Dari hasil pengujian pada tabel 4.11, dapat diketahui bahwa sensor kecepatan nilai maksimum kecepatan putaran motor hidrolik pada saat berputar kearah kanan adalah 201 Rpm pada tegangan keluaran generator DC -3,521 V sedangkan nilai maksimum kecepatan putaran motor hidrolik pada saat berputar kearah kiri adalah 175 Rpm pada tegangan keluaran generator DC +3,551V. nilai minimum atau pada saat keadaan berhenti kecepatan pada kedua arah tersebut adalah 0V

4.7 Pengujian Integrasi Semua Perlatan Secara Keseluruhan

Pada pengujian sistem secara keseluruhan, semua perangkat driver servo valve yang terdiri atas rangkaian rangkaian Zero-span, rangkaian push pull komplementer, rangkaian modul DAC, dan sensor kecepatan. Pengujian ini dilakukan untuk mengetahui kinerja dari kinerja pada keseluruhan rangkaian pada sistem.

Tabel 4.13 tabel hasil pengukuran seluruh rangkaian dan sensor kecepatan

Nilai diskrit DAC	Vout DAC (V)	Vout rangkaian driver servo valve (V)	Vout Sensor putaran generator dc (V)	Kecepatan (RPM)	Arah Putar
0	0	-1,68	3,55	175	kiri
25	0,02	-1,578	3,51	170	kiri
832	0,67	-0,557	2,1	100	kiri
1100	0,88	-0,313	0,299	78	kiri
1250	1	-0,275	1,075	55	kiri
1500	1,2	-0,1	0,91	48	kiri
1875	1,5	-0,0091	0,915	48	kiri
2000	1,6	-0,0073	0,7	10,4	kiri

2125	1,7	-0,0051	0,65	34	kiri
2250	1,8	0,0021	0,4	10,4	kiri
2435	1,948	0	0	0	Tidak berputa r
2625	2,1	0,655	-0,33	26	Kanan
2750	2,2	0,805	-0,9	49,7	Kanan
2875	2,3	0,809	-1,02	57,9	Kanan
3000	2,4	1,12	-1,82	90,2	Kanan
3125	2,5	1,28	-2,087	102,5	Kanan
3250	2,6	1,44	-2,43	139,2	Kanan
3375	2,7	1,59	-2,78	156,2	Kanan
3500	2,8	1,746	-3,17	175,2	Kanan
3625	2,9	1,89	-3,24	182	Kanan
3750	3,05	1,98	-3,44	195	Kanan
3875	3,1	2,08	-3,45	197	Kanan
4000	3,19	2,18	-3,521	201	Kanan
4095	3,3	2,18	-3,521	201	Kanan

Dari hasil pada tabel 4.12 dapat dilihat bahwa sistem berjalan sudah hampir mendekati yang diinginkan yaitu mengatur kecepatan dengan menggunakan nilai DAC yang diperintahkan oleh mikrokontroller. Servo valve akan menahan aliran oli dan tidak menggerakkan sama sekali motor hidrolik pada tegangan DAC 1,948V dengan nilai diskrit 2435.

BAB V
PENUTUP

5.1 Kesimpulan

Setelah melakukan tahap perancangan dan pembuatan sistem yang kemudian dilanjutkan dengan tahap pengujian dan analisa maka dapat diambil kesimpulan sebagai berikut:

- Modul *Elektro Hidrolik Servomechanism* (EHS 160) telah bekerja dan dapat dikendalikan menggunakan mikrokontroller dan rangkaian driver servo valve amplifier yang terdiri atas rangkaian *zero-span* dan rangkaian *push-pull* komplementer.
- Pada perancangan driver servo valve arus yang dibutuhkan dari -100mA hingga +100mA, dengan keterangan tersebut perancangan yang telah dibuat pada proses perancangan cukup berhasil mengendalikan servo valve walaupun arus yang dihasilkan mendekati hasil yang diinginkan yaitu dengan -85mA hinggan +80mA. Dengan batas tegangan masuk pada servo valve adalah (-2) V – (+2) V, maka rangkaian zero-span dapat digunakan sebagai pilihan untuk mengkonversi tegangan yang kita inginkan.

5.2 Saran

1. Masih banyak kekurangan dari tugas akhir ini seperti sensor yang digunakan hanya satu yaitu sensor kecepatan yang menggunakan motor DC sebagai Tachometer. Sedangkan sensor yang belum terbaca adalah sensor posisi dan tiga sensor tekanan lainnya. Jika ingin menggunakan modul hidrolik ini untuk mengambil data posisi dan tekanan disarankan untuk melanjutkan penelitian dengan mengambil topik pembacaan sensor posisi dan tekanan pada modul hidrolik ini.
2. Pada pencarian data alat atau datasheet peralatan yang ada pada modul ini terdapat kesulitan, yaitu tidak adanya datasheet servo valve dan hanya dapat dibaca kasar pada buku petunjuk penggunaan EHS160, yang mengkibatkan

lamanya proses identifikasi terhadap servo valve. Untuk itu disarankan agar pada penelitian selanjutnya melengkapi data yang belum ada, seperti sensor posisi dengan syncronous, sensor tekanan, sensor aliran, jenis air dryer, dan rangkaian elektro mekanik EHS 160.

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LAMPIRAN
DATASHEET

A. *Datasheet DAC MCP4725.*

MICROCHIP

MCP4725

12-Bit Digital-to-Analog Converter with EEPROM Memory in SOT-23-6

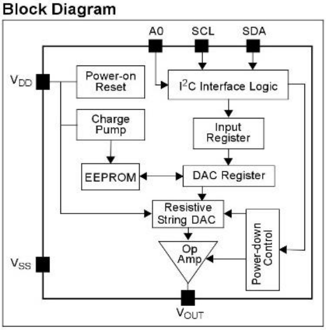
Features

- 12-Bit Resolution
- On-Board Non-Volatile Memory (EEPROM)
- ±0.2 LSB DNL (typical)
- External A0 Address Pin
- Normal or Power-Down Mode
- Fast Settling Time of 6 µs (typical)
- External Voltage Reference (V_{DD})
- Rail-to-Rail Output
- Low Power Consumption
- Single-Supply Operation: 2.7V to 5.5V
- I^2C^{TM} Interface:
  - Eight Available Addresses
  - Standard (100 kbps), Fast (400 kbps), and High-Speed (3.4 Mbps) Modes
- Small 6-lead SOT-23 Package
- Extended Temperature Range: -40°C to +125°C

Applications

- Set Point or Offset Trimming
- Sensor Calibration
- Closed-Loop Servo Control
- Low Power Portable Instrumentation
- PC Peripherals
- Data Acquisition Systems

Block Diagram



DESCRIPTION

The MCP4725 is a low-power, high accuracy, single channel, 12-bit buffered voltage output Digital-to-Analog Convertor (DAC) with non-volatile memory (EEPROM). Its on-board precision output amplifier allows it to achieve rail-to-rail analog output swing.

The DAC input and configuration data can be programmed to the non-volatile memory (EEPROM) by the user using I^2C interface command. The non-volatile memory feature enables the DAC device to hold the DAC input code during power-off time, and the DAC output is available immediately after power-up. This feature is very useful when the DAC device is used as a supporting device for other devices in the network.

The device includes a Power-On-Reset (POR) circuit to ensure reliable power-up and an on-board charge pump for the EEPROM programming voltage. The DAC reference is driven from VDD directly. In power-down mode, the output amplifier can be configured to present a low, medium, or high resistance output load.

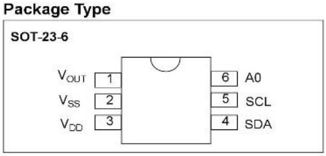
The MCP4725 has an external A0 address pin. This A0 pin can be tied to VDD or VSS of the user's application board.

The MCP4725 has a two-wire I^2C™ compatible serial interface for standard (100 kHz), fast (400 kHz), or high speed (3.4 MHz) mode.

The MCP4725 is an ideal DAC device where design simplicity and small footprint is desired, and for applications requiring the DAC device settings to be saved during power-off time.

The device is available in a small 6-pin SOT-23 package.

Package Type



PRODUCT IDENTIFICATION SYSTEM

To order or obtain information, e.g., on pricing or delivery, refer to the factory or the listed sales office.

PART NO.	XX	X	X	/XX
Device	Address Options	Tape and Reel	Temperature Range	Package

Device: MCP4725: Single Channel 12-Bit DAC w/EEPROM Memory

Address Options:

XX		A2	A1	A0
A0 *	=	0	0	External
A1	=	0	1	External
A2	=	1	0	External
A3	=	1	1	External

* Default option. Contact Microchip factory for other address options

Tape and Reel: T = Tape and Reel

Temperature Range: E = -40°C to +125°C

Package: CH = Plastic Small Outline Transistor (SOT-23-6), 6-lead

Examples:

a) MCP4725A0T-E/CH: Tape and Reel, Extended Temp., 6LD SOT-23 pkg. Address Option = A0

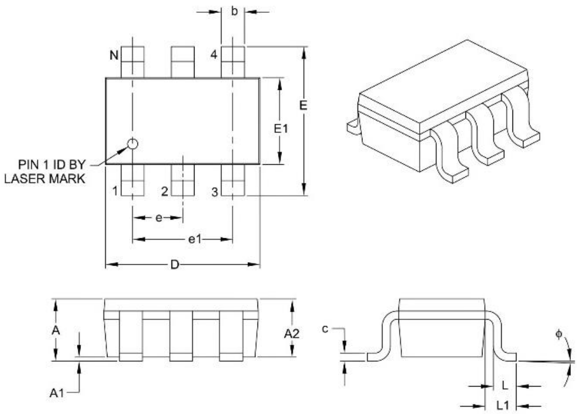
b) MCP4725A1T-E/CH: Tape and Reel, Extended Temp., 6LD SOT-23 pkg. Address Option = A1

c) MCP4725A2T-E/CH: Tape and Reel, Extended Temp., 6LD SOT-23 pkg. Address Option = A2

d) MCP4725A3T-E/CH: Tape and Reel, Extended Temp., 6LD SOT-23 pkg. Address Option = A3

6-Lead Plastic Small Outline Transistor (CH) [SOT-23]

Note: For the most current package drawings, please see the Microchip Packaging Specification located at http://www.microchip.com/packaging



	Units	MILLIMETERS		
	Dimension Limits	MIN	NOM	MAX
Number of Pins	N		6	
Pitch	e		0.95 BSC	
Outside Lead Pitch	e1		1.90 BSC	
Overall Height	A	0.90	–	1.45
Molded Package Thickness	A2	0.89	–	1.30
Standoff	A1	0.00	–	0.15
Overall Width	E	2.20	–	3.20
Molded Package Width	E1	1.30	–	1.80
Overall Length	D	2.70	–	3.10
Foot Length	L	0.10	–	0.60
Footprint	L1	0.35	–	0.80
Foot Angle	ϕ	0°	–	30°
Lead Thickness	c	0.08	–	0.26
Lead Width	b	0.20	–	0.51

Notes:

1. Dimensions D and E1 do not include mold flash or protrusions. Mold flash or protrusions shall not exceed 0.127 mm per side.
2. Dimensioning and tolerancing per ASME Y14.5M.

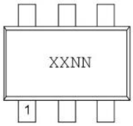
   BSC: Basic Dimension. Theoretically exact value shown without tolerances.

Microchip Technology Drawing C04-028B

10.0 PACKAGING INFORMATION

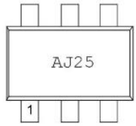
10.1 Package Marking Information

6-Lead SOT-23



Part Number	Address Option	Code
MCP4725A0T-E/CH	A0 (00)	AJNN
MCP4725A1T-E/CH	A1 (01)	APNN
MCP4725A2T-E/CH	A2 (10)	AQNN
MCP4725A3T-E/CH	A3 (11)	ARNN

Example



Legend:

XX...X	Customer-specific information
Y	Year code (last digit of calendar year)
YY	Year code (last 2 digits of calendar year)
WW	Week code (week of January 1 is week '01')
NNN	Alphanumeric traceability code
e3	Pb-free JEDEC designator for Matte Tin (Sn)
*	This package is Pb-free. The Pb-free JEDEC designator (e3) can be found on the outer packaging for this package.

Note: In the event the full Microchip part number cannot be marked on one line, it will be carried over to the next line, thus limiting the number of available characters for customer-specific information.

9.0 DEVELOPMENT SUPPORT

9.1 Evaluation & Demonstration Boards

The MCP4725 SOT-23-6 Evaluation Board is available from Microchip Technology Inc. This board works with Microchip's PICkit™ Serial Analyzer. The user can program the DAC input codes and EEPROM data, or read the programmed data using the easy to use PICkit Serial Analyzer with the Graphic User Interface software. Refer to www.microchip.com for further information on this product's capabilities and availability.

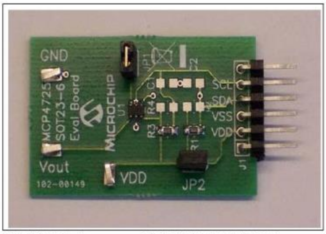


FIGURE 9-1: MCP4725 SOT-23-6 Evaluation Board.

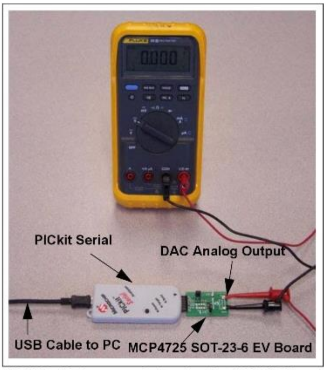


FIGURE 9-2: Setup for the MCP4725 SOT-23-6 Evaluation Board with PICkit™ Serial Analyzer.

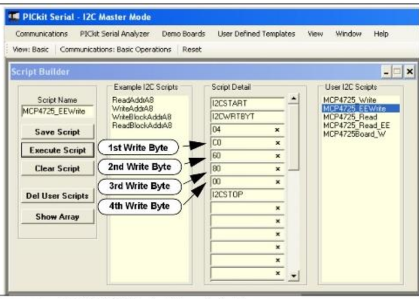


FIGURE 9-3: Example of PICkit™ Serial User Interface.

8.5.4.1 Design a Bipolar DAC using Example 8-3

Some applications desires an output step magnitude of 1 mV with an output range of ±2.05V. The following steps explain the design solution:

1. Calculate the range: +2.05V – (-2.05V) = 4.1V.
2. Calculate the resolution needed:
   4.1V/1 mV = 4100

   Since 2^{12} = 4096 for 12-bit resolution.
3. The amplifier gain (R_2/R_1), multiplied by V_{DD}, must be equal to the desired minimum output to achieve bipolar operation. Since any gain can be realized by choosing resistor values (R_1+R_2), the V_{DD} value must be selected first. If a V_{DD} of 4.1V is used, solve for the amplifier's gain by setting the DAC to 0, knowing that the output needs to be -2.05V. The equation can be simplified to:

$$\frac{-R_2}{R_1} = \frac{-2.05}{V_{DD}} = \frac{-2.05}{4.1} \rightarrow \frac{R_2}{R_1} = \frac{1}{2}$$

If R_1 = 20 kΩ and R_2 = 10 kΩ, the gain will be 0.5.

4. Next, solve for R_3 and R_4 by setting the DAC to 4096, knowing that the output needs to be +2.05V.

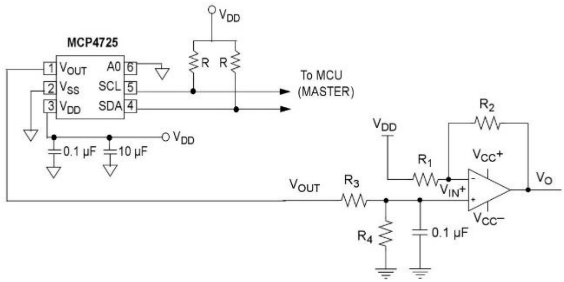
$$\frac{R_4}{(R_3 + R_4)} = \frac{2.05V + (0.5 \cdot V_{DD})}{1.5 \cdot V_{DD}} = \frac{2}{3}$$

If R_4 = 20 kΩ, then R_3 = 10 kΩ

8.5.4 BIPOLAR OPERATION

Bipolar operation is achievable using the MCP4725 by using an external operational amplifier (op amp). This allows a general purpose DAC, with its cost and availability advantages, to meet almost any desired output voltage range, power and noise performance.

Example 8-3 illustrates a simple bipolar voltage source configuration. R_1 and R_2 allow the gain to be selected, while R_3 and R_4 shift the DAC's output to a selected offset. Note that R4 can be tied to V_{DD} (= V_{REF}) instead of V_{SS}, if a higher offset is desired. Note that a pull-up to V_{DD} could be used, instead of R_4, if a higher offset is desired.



$$V_{OUT} = V_{DD}\frac{D}{2^{12}}$$ where D = DAC Input Code (0 – 4095)

$$V_{IN+} = \frac{V_{OUT}R_4}{R_3 + R_4}$$

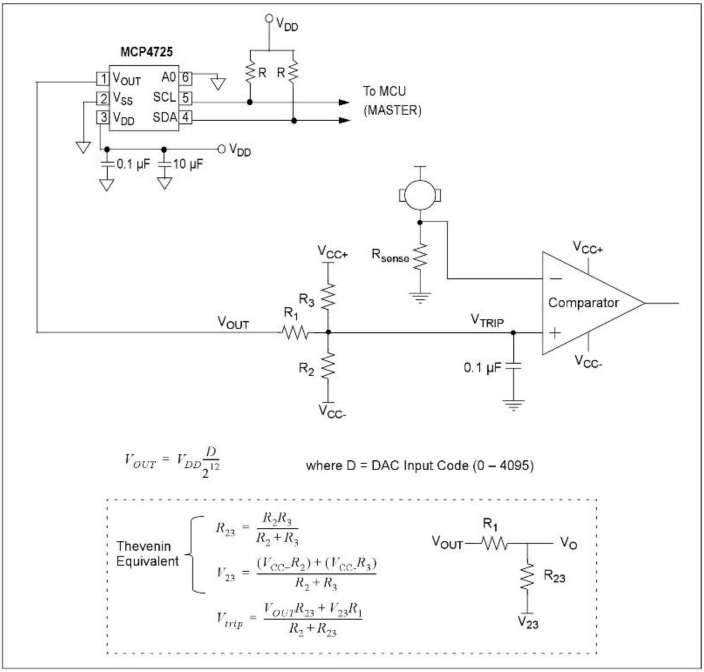
$$V_O = V_{IN+}\left(1 + \frac{R_2}{R_1}\right) - V_{DD}\left(\frac{R_2}{R_1}\right)$$

EXAMPLE 8-3: *Digitally-Controlled Bipolar Voltage Source.*

8.5.3 BUILDING A "WINDOW" DAC

Some sensor applications require very high resolution around the set point or threshold voltage.

Example 8-2 shows an example of creating a "window" around the threshold using a voltage divider network with a pull-up and pull-down resistor. In the circuit, the output voltage range is scaled down, but its step resolution is increased greatly.

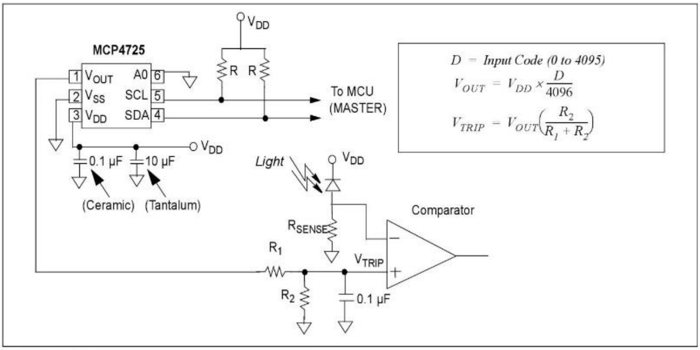


EXAMPLE 8-2: *Single-Supply "Window" DAC.*

8.5.2 DECREASING THE OUTPUT STEP SIZE

Calibrating the threshold of a diode, transistor or resistor may require a very small step size in the DAC output voltage. These applications may require about 200 µV of step resolution within 0.8V of range.

One method of achieving this small step resolution is using a voltage divider at the DAC output. An example is shown in Example 8-1. The step size of the DAC output is scaled down by the factor of the ratio of the voltage divider. Note that the bypass capacitor on the output of the voltage divider plays a critical function in attenuating the output noise of the DAC and the induced noise from the environment.



EXAMPLE 8-1: *Set Point Or Threshold Calibration.*

8.2 Using Non-Volatile EEPROM Memory

The user can store the DAC input code (12 bits) and power-down configuration bits (2 bits) in the internal non-volatile EEPROM memory using the I^2C write command. The user can also read the EEPROM data using the I^2C read command. When the device is first powered after power is shut down, the device uploads the EEPROM contents to the DAC register automatically and provides the DAC output immediately. This feature is very useful in applications where the DAC device is used to provide set point or calibration data for other devices in the application system. The DAC will not lose the important system operational parameters due to the system power failure incidents. See **Section 5.6 "Non-Volatile EEPROM Memory"** for more details of the non-volatile EEPROM memory.

8.3 Power Supply Considerations

The power supply to the device is used for both V_{DD} and DAC reference voltage. Any noise induced on the V_{DD} line can affect on the DAC performance. Typical application will require a bypass capacitor in order to filter out high frequency noise on the V_{DD} line. The noise can be induced onto the power supply's traces or as a result of changes on the DAC output. The bypass capacitor helps to minimize the effect of these noise sources on signal integrity. Figure 8-1 shows an example of using two bypass capacitors (a 10 µF tantalum capacitor and a 0.1 µF ceramic capacitor) in parallel on the V_{DD} line. These capacitors should be placed as close to the V_{DD} pin as possible (within 4 mm).

The power source should be as clean as possible. If the application circuit has separate digital and analog power supplies, the V_{DD} and V_{SS} pins of the MCP4725 should reside on the analog plane.

8.4 Layout Considerations

Inductively-coupled AC transients and digital switching noise from other devices can affect on DAC performance and DAC output signal integrity. Careful board layout will minimize these effects. Bench testing has shown that a multi-layer board utilizing a low-inductance ground plane, isolated inputs, isolated outputs and proper decoupling are critical to achieving the performance that the MCP4725 is capable of providing. Particularly harsh environments may require shielding of critical signals. Separate digital and analog ground planes are recommended. In this case, the V_{SS} pin and the ground pins of the V_{DD} capacitors of the MCP4725 should be terminated to the analog ground plane.

8.5 Application Examples

The MCP4725 is a rail-to-rail output DAC designed to operate with a V_{DD} range of 2.7V to 5.5V. Its output amplifier is robust enough to drive common, small-signal loads directly, thus eliminating the cost and size of an external buffer for most applications.

8.5.1 DC SET POINT OR CALIBRATION

A common application for the MCP4725 is a digitally-controlled set point or a calibration of variable parameters such as sensor offset or bias point. Example 8-1 shows an example of the set point setting. Since the MCP4725 is a 12-bit DAC and uses the V_{DD} supply as a reference source, it provides a $V_{DD}/4096$ of resolution per step.

8.0 TYPICAL APPLICATIONS

The MCP4725 device is one of Microchip's latest DAC device family with non-volatile EEPROM memory. The device is a general purpose resistive string DAC intended to be used in applications where a precision, and low power DAC with moderate bandwidth is required.

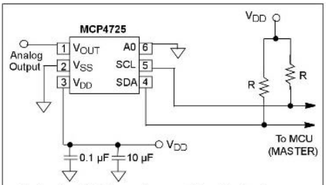
Since the device includes non-volatile EEPROM memory, the user can use this device for applications that require the output to return to the previous set-up value on subsequent power-ups.

Applications generally suited for the MCP4725 device family include:

- Set Point or Offset Trimming
- Sensor Calibration
- Portable Instrumentation (Battery Powered)
- Motor Speed Control

8.1 Connecting to I²C BUS using Pull-Up Resistors

The SCL and SDA pins of the MCP4725 are open-drain configurations. These pins require a pull-up resistor as shown in Figure 8-1. The value of these pull-up resistors depends on the operating speed (standard, fast, and high speed) and loading capacitance of the I²C bus line. Higher value of pull-up resistor consumes less power, but increases the signal transition time (higher RC time constant) on the bus. Therefore, it can limit the bus operating speed. The lower resistor value, on the other hand, consumes higher power, but allows higher operating speed. If the bus line has higher capacitance due to long bus line or high number of devices connected to the bus, a smaller pull-up resistor is needed to compensate the long RC time constant. The pull-up resistor is typically chosen between 1 kΩ and 10 kΩ ranges for standard and fast modes, and less than 1 kΩ for high speed mode.



Note 1: R is the pull-up resistor. Typically 1 ~ 10 kΩ

2: A0 can be tied to V_{SS}, V_{DD} or driven by MCU

FIGURE 8-1: *I²C Bus Interface Connection with A0 pin tied to V_{SS}.*

Two devices with the same A2 and A1 address bits can be connected to the same I²C bus by utilizing the A0 address pin (Example: A0 pin of device A is tied to V_{DD}, and the other device's pin is tied to V_{SS}.)

8.1.1 DEVICE CONNECTION TEST

The user can test the presence of the MCP4725 on the I²C bus line without performing the data conversion. This test can be achieved by checking an acknowledge response from the MCP4725 after sending a read or write command. Here is an example using Figure 8-2:

(a) Set the R/$\overline{W}$ bit "HIGH" in the address byte.

(b) If the MCP4725 is connected to the I²C bus line, it will then acknowledge by pulling SDA bus LOW during the ACK clock and then release the bus back to the I²C Master.

(c) A STOP or repeated START bit can then be issued from the Master and I²C communication can continue.

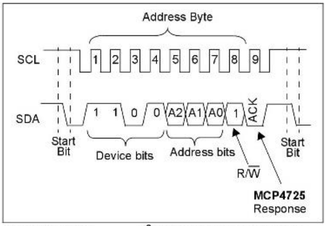


FIGURE 8-2: *I²C Bus Connection Test.*

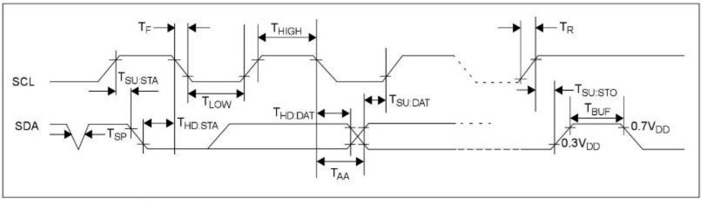


FIGURE 7-4: *I^2C Bus Timing Data.*

TABLE 7-1: I²C SERIAL TIMING SPECIFICATIONS (CONTINUED)

Electrical Specifications: Unless otherwise specified, all limits are specified for T_A = -40 to +85°C, V_{DD} = +2.7V to +5.0V, V_{SS} = 0V.						
Parameters	**Sym**	**Min**	**Typ**	**Max**	**Units**	**Conditions**
High Speed Mode (Note 5)						
Clock frequency	f_{SCL}	0	—	3.4 1.7	MHz MHz	C_b = 100 pF C_b = 400 pF
Clock high time	T_{HIGH}	60 120	—	—	ns ns	C_b = 100 pF C_b = 400 pF
Clock low time	T_{LOW}	160 320	—	—	ns	C_b = 100 pF C_b = 400 pF
SCL rise time **(Note 1)**	T_R	—	—	40 80	ns	From V_{IL} to V_{IH}, C_b = 100 pF C_b = 400 pF
SCL fall time **(Note 1)**	T_F	—	—	40 80	ns	From V_{IH} to V_{IL}, C_b = 100 pF C_b = 400 pF
SDA rise time **(Note 1)**	$T_{R:DAT}$	—	—	80 160	ns	From V_{IL} to V_{IH}, C_b = 100 pF C_b = 400 pF
SDA fall time **(Note 1)**	$T_{F:DATA}$	—	—	80 160	ns	From V_{IH} to V_{IL}, C_b = 100 pF C_b = 400 pF
START condition hold time	$T_{HD:STA}$	160	—	—	ns	After this period, the first clock pulse is generated
Repeated START condition setup time	$T_{SU:STA}$	160	—	—	ns	Only relevant for repeated Start condition
Data hold time **(Note 4)**	$T_{HD:DAT}$	0 0	—	70 150	ns	C_b = 100 pF C_b = 400 pF
Data input setup time	$T_{SU:DAT}$	10	—	—	ns	
STOP condition setup time	$T_{SU:STO}$	160	—	—	ns	
STOP condition hold time	$T_{HD:STD}$	160	—	—	ns	
Output valid from clock **(Notes 2 and 3)**	T_{AA}	—	—	150 310	ns	C_b = 100 pF C_b = 400 pF
Bus free time	T_{BUF}	160	—	—	ns	Time between START and STOP conditions.

Note 1: This parameter is ensured by characterization and not 100% tested.

2: This specification is not a part of the I2C specification. This specification is equivalent to the Data Hold Time ($T_{HD:DAT}$) plus SDA Fall (or rise) time: $T_{AA} = T_{HD:DAT} + T_F$ (OR T_R).

3: If this parameter is too short, it can create an unintended Start or Stop condition to other devices on the bus line. If this parameter is too long, Clock Low time (T_{LOW}) can be affected.

4: For Data Input: This parameter must be longer than t_{SP}. If this parameter is too long, the Data Input Setup ($T_{SU:DAT}$) or Clock Low time (T_{LOW}) can be affected.
For Data Output: This parameter is characterized, and tested indirectly by testing T_{AA} parameter.

5: All timing parameters in high-speed modes are tested at V_{DD} = 5V.

TABLE 7-1: I^2C SERIAL TIMING SPECIFICATIONS

Electrical Specifications: Unless otherwise specified, all limits are specified for T_A = -40 to +85°C, V_{DD} = +2.7V to +5.0V, V_{SS} = 0V.

Parameters	Sym	Min	Typ	Max	Units	Conditions
Standard Mode						
Clock frequency	f_{SCL}	0	—	100	kHz	
Clock high time	T_{HIGH}	4000	—	—	ns	
Clock low time	T_{LOW}	4700	—	—	ns	
SDA and SCL rise time **(Note 1)**	T_R	—	—	1000	ns	From V_{IL} to V_{IH}
SDA and SCL fall time **(Note 1)**	T_F	—	—	300	ns	From V_{IH} to V_{IL}
START condition hold time	$T_{HD:STA}$	4000	—	—	ns	After this period, the first clock pulse is generated.
Repeated START condition setup time	$T_{SU:STA}$	4700	—	—	ns	Only relevant for repeated Start condition
Data hold time **(Note 3)**	$T_{HD:DAT}$	0	—	3450	ns	
Data input setup time	$T_{SU:DAT}$	250	—	—	ns	
STOP condition setup time	$T_{SU:STO}$	4000	—	—	ns	
STOP condition hold time	$T_{HD:STD}$	4000	—	—	ns	
Output valid from clock **(Notes 2 and 3)**	T_{AA}	0	—	3750	ns	
Bus free time	T_{BUF}	4700	—	—	ns	Time between START and STOP conditions.
Fast Mode						
Clock frequency	T_{SCL}	0	—	400	kHz	
Clock high time	T_{HIGH}	600	—	—	ns	
Clock low time	T_{LOW}	1300	—	—	ns	
SDA and SCL rise time **(Note 1)**	T_R	20 + 0.1Cb	—	300	ns	From V_{IL} to V_{IH}
SDA and SCL fall time **(Note 1)**	T_F	20 + 0.1Cb	—	300	ns	From V_{IH} to V_{IL}
START condition hold time	$T_{HD:STA}$	600	—	—	ns	After this period, the first clock pulse is generated
Repeated START condition setup time	$T_{SU:STA}$	600	—	—	ns	Only relevant for repeated Start condition
Data hold time **(Note 4)**	$T_{HD:DAT}$	0	—	900	ns	
Data input setup time	$T_{SU:DAT}$	100	—	—	ns	
STOP condition setup time	$T_{SU:STO}$	600	—	—	ns	
STOP condition hold time	$T_{HD:STD}$	600	—	—	ns	
Output valid from clock **(Notes 2 and 3)**	T_{AA}	0	—	1200	ns	
Bus free time	T_{BUF}	1300	—	—	ns	Time between START and STOP conditions.

Note 1: This parameter is ensured by characterization and not 100% tested.

2: This specification is not a part of the I2C specification. This specification is equivalent to the Data Hold Time ($T_{HD:DAT}$) plus SDA Fall (or rise) time: $T_{AA} = T_{HD:DAT} + T_F$ (OR T_R).

3: If this parameter is too short, it can create an unintended Start or Stop condition to other devices on the bus line. If this parameter is too long, Clock Low time (T_{LOW}) can be affected.

4: For Data Input: This parameter must be longer than t_{SP}. If this parameter is too long, the Data Input Setup ($T_{SU:DAT}$) or Clock Low time (T_{LOW}) can be affected.
For Data Output: This parameter is characterized, and tested indirectly by testing T_{AA} parameter.

5: All timing parameters in high-speed modes are tested at V_{DD} = 5V.

7.5.5 ACKNOWLEDGE

Each receiving device, when addressed, is obliged to generate an acknowledge after the reception of each byte. The master device must generate an extra clock pulse which is associated with this acknowledge bit.

The device that acknowledges, has to pull down the SDA line during the acknowledge clock pulse in such a way that the SDA line is stable LOW during the HIGH period of the acknowledge related clock pulse. Of course, setup and hold times must be taken into account. During reads, a master must send an end of data to the slave by not generating an acknowledge bit on the last byte that has been clocked out of the slave.

In this case, the slave (MCP4725) will leave the data line HIGH to enable the master to generate the STOP condition.

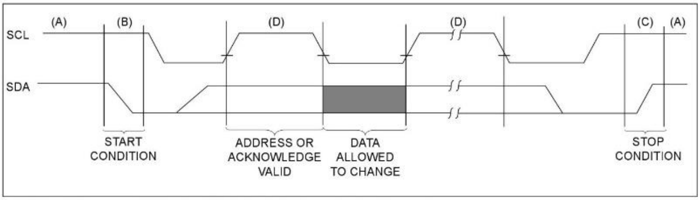


FIGURE 7-3: *Data Transfer Sequence On The Serial Bus.*

7.0 I²C SERIAL INTERFACE COMMUNICATION

7.1 OVERVIEW

The MCP4725 device uses a two-wire I²C serial interface that can operate on a standard, fast or high speed mode. A device that sends data onto the bus is defined as transmitter, and a device receiving data as receiver. The bus has to be controlled by a master device which generates the serial clock (SCL), controls the bus access and generates the START and STOP conditions. The MCP4725 device works as slave. Both master and slave can operate as transmitter or receiver, but the master device determines which mode is activated. An example of hardware connection diagram is shown in Figure 8-1. Communication is initiated by the master (microcontroller) which sends the START bit, followed by the slave address byte. The first byte transmitted is always the slave address byte, which contains the device code, the address bits, and the R/$\overline{W}$ bit. The device code for the MCP4725 device is `1100`.

When the device receives a read command (R/W = `1`), it transmits the contents of the DAC input register and EEPROM. A non-acknowledge (NAK) or repeated start bit can be transmitted at any time. See Figure 6-3 for the read operation example. If writing to the device (R/W = `0`), the device will expect write command type bits in the following byte. See Figure 6-1 and Figure 6-2 for the write operation examples.

The MCP4725 supports all three I²C operating modes:

- Standard Mode: bit rates up to 100 kbit/s
- Fast Mode: bit rates up to 400 kbit/s
- High Speed Mode (HS mode): bit rates up to 3.4 Mbit/s

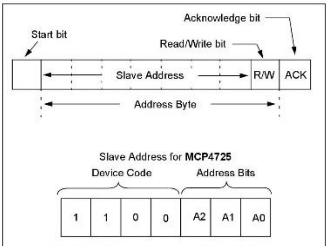
Refer to the Phillips I²C document for more details of the I²C specifications.

7.2 Device Addressing

The address byte is the first byte received following the START condition from the master device. The first part of the address byte consists of a 4-bit device code which is set to `1100` for the MCP4725. The device code is followed by three address bits (A2, A1, A0) which are programmed as follows:

- The choice of A2 and A1 bits are provided by the customer as part of the ordering process. These bits are then programmed (hard-wired) during manufacturing
- The A2 and A1 are programmed to '`00`' (default), if not requested by customer
- A0 bit is determined by the logic state of A0 pin. The A0 pin can be tied to V_{DD} or V_{SS}, or can be actively driven by digital logic levels. The advantage of using the A0 pin is that the users can control the A0 bit on their application PCB circuit and also two identical MCP4725 devices can be used on the same bus line.

When the device receives an address byte, it compares the logic state of the A0 pin with the A0 address bit received before responding with the acknowledge bit. The logic state of the A0 pin needs to be set prior to the interface communication.

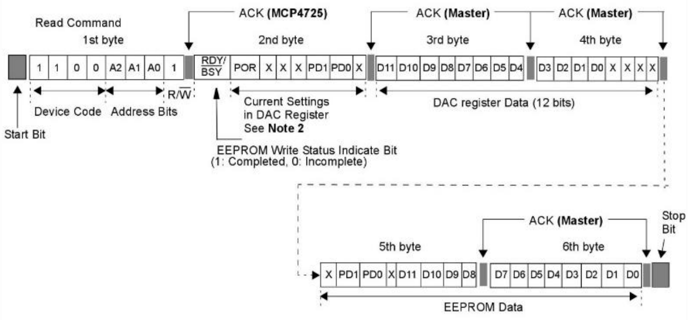


Note: A2 and A1: Programmed (hard-wired) at the factory. Please Contact Microchip Technology Inc. for A2 and A1 programming options.
A0: Use the logic level state of A0 pin.

FIGURE 7-1: *Device Addressing*

6.2 READ COMMAND

If the R/$\overline{W}$ bit is set to a logic "high", then the device outputs on SDA pin, the DAC register and EEPROM data. Figure 6-3 shows an example of reading the register and EEPROM data. The 2nd byte in Figure 6-3 indicates the current condition of the device operation. The RDY/$\overline{BSY}$ bit indicates EEPROM writing status. The RDY/$\overline{BSY}$ bit stays low during EEPROM writng and high when the writing is completed..



Note 1: Bytes 2 - 6 are repeated in repeat bytes after byte 6.

2: X is don't care bit.

FIGURE 6-3: *Read Command and Output Data Format.*

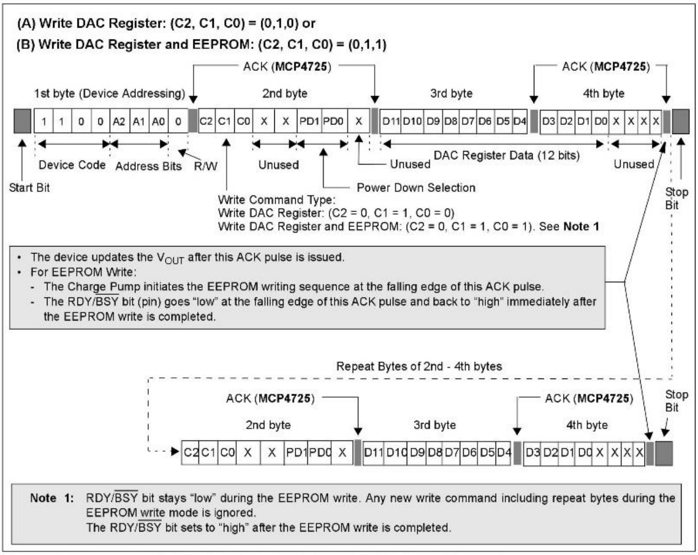


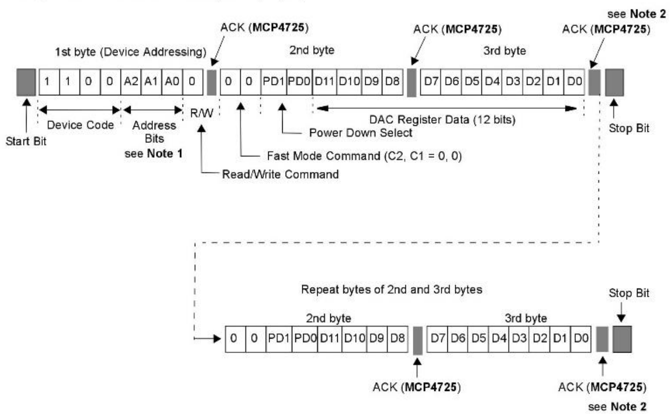
FIGURE 6-2: *Write Commands for DAC Input Register and EEPROM.*

TABLE 6-2: WRITE COMMAND TYPE

C2	C1	C0	Command Name	Function
0	0	X	Fast Mode	This command is used to change the DAC register. EEPROM is not affected
0	0	X	"	"
0	1	0	Write DAC Register	Load configuration bits and data code to the DAC Register
0	1	1	Write DAC Register and EEPROM	(a) Load configuration bits and data code to the DAC Register and (b) also write the EEPROM
1	0	0	Reserved	Reserved for future use
1	0	1	Reserved	Reserved for future use
1	1	0	Reserved	Reserved for future use
1	1	1	Reserved	Reserved for future use

Note 1: X = Dont' Care. Fast Mode does not use C0 bit.

2: The MCP4725 ignores the "Reserved" commands.



Note 1: A2 and A1 bits are programmed at the factory by hard-wired, and A0 bit is determined by the logic state of A0 pin.

2: The device updates V_{OUT} at the falling edge of the ACK pulse of the 3rd byte.

FIGURE 6-1: *Write Command for Fast Mode.*

6.0 THEORY OF OPERATION

When the device is connected to the I²C bus line, the device is working as a slave device. The Master (MCU) can write/read the DAC input register or EEPROM using the I²C interface command. The MCP4725 device address contains four fixed bits (`1100` = device code) and three address bits (A2, A1, A0). The A2 and A1 bits are hard-wired during manufacturing, and A0 bit is determined by the logic state of A0 pin. The A0 pin can be connected to V_{DD} or V_{SS}, or actively driven by digital logic levels.

The following sections describe the communication protocol to send or read the data code and write/read the EEPROM using the I²C interface. See **Section 7.0 "I²C Serial Interface Communication"**.

6.1 Write Commands

The write commands are used to load the configuration bits and DAC input code to the DAC register, or to write to the EEPROM of the device. The write command types are defined by using three write command type bits (C2, C1, C0). Table 6-2 shows the write command types and their functions. There are three command types for the MCP4725. The four "reserved" commands in Table 6-2 are for future use. The MCP4725 ignores the "reserved" commands. Write command protocol examples are shown in Figure 6-1 and Figure 6-2.

The input data code is coded as shown in Table 6-1. The MSB of the data is always transmitted first and the format is unipolar binary.

TABLE 6-1: INPUT DATA CODING

Input Code	Nominal Output Voltage (V)
`111111111111` (FFFh)	V_{DD} - 1 LSB
`111111111110` (FFEh)	V_{DD} - 2 LSB
`000000000010` (002h)	2 LSB
`000000000001` (001h)	1 LSB
`000000000000` (000h)	0

6.1.1 WRITE COMMAND FOR FAST MODE (C2 = 0, C1 = 0, C0 = X, X = DON'T CARE)

The fast write command is used to update the DAC register. The data in the EEPROM of the device is not affected by this command. This command updates Power-Down mode selection bits (PD1 and PD0) and 12 bits of the DAC input code in the DAC register. Figure 6-1 shows an example of the fast write command for the MCP4725 device.

6.1.2 WRITE COMMAND FOR DAC INPUT REGISTER (C2 = 0, C1 = 1, C0 = 0)

In MCP4725, this command performs the same function as the Fast Mode command in **Section 6.1.1 "Write Command for Fast mode (C2 = 0, C1 = 0, C0 = X, X = Don't Care)"**. Figure 6-2 shows the write command protocol for the MCP4725.

As shown in Figure 6-2, the D11 - D0 bits in the third and fourth bytes are DAC input data. The last 4 bits (X, X, X, X) in the fourth byte are don't care bits.

The device executes the Master's write command after receiving the last byte (4th byte). The Master can send a STOP bit to terminate the current sequence, or send a Repeated START bit followed by an address byte. If the device receives three data bytes continuously after the 4th byte, it updates from the 2nd to the 4th data bytes with the last three input data bytes.

The contents of the register are updated at the end of the 4th byte. The device ignores any partially received data bytes if the I²C communication with the Master ends before completing the 4th byte.

6.1.3 WRITE COMMAND FOR DAC INPUT REGISTER AND EEPROM (C2 = 0, C1 = 1, C0 = 1)

When the device receives this command, it (a) loads the configuration and data bits to the DAC register, and (b) also writes the EEPROM. When the device is writing the EEPROM, the RDY/$\overline{BSY}$ bit goes low and stays low until the EEPROM write operation is completed. The state of the RDY/$\overline{BSY}$ bit can be monitored by a read command. Figure 6-2 shows the details of the this write command protocol and Figure 6-3 shows the details of the read command.

5.6 Non-Volatile EEPROM Memory

The MCP4725 device has a 14-bit wide EEPROM memory to store configuration bit (2 bits) and DAC input data (12 bits). These bits are readable and re-writable with I^2C interface commands. The device has an on-chip charge pump circuit to write the EEPROM memory bits without using an external program voltage.

The EEPROM writing operation is initiated when the device receives an EEPROM write command (C2 = 0, C1 = 1, C0 = 1). The configuration and writing data bits are transferred to the EEPROM memory block. A status bit, $RDY/\overline{BSY}$, stays low during the EEPROM writing and goes high as the write operation is completed. While the $RDY/\overline{BSY}$ bit is low (during the EEPROM writing), any new write command is ignored (for EEPROM or DAC register). Table 5-3 shows the EEPROM bits and factory default settings. Table 5-4 shows the DAC input register bits of the MCP4725.

TABLE 5-3: EEPROM MEMORY AND FACTORY DEFAULT SETTINGS (TOTAL NUMBER OF BITS: 14 BITS)

Bit Name	PD1	PD0	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
Bit Function	Power-Down Select (2 bits)		DAC Input Data (12 bits)											
Factory Default Value	0	0 (1)	1 (2)	0	0	0	0	0	0	0	0	0	0	0

Note 1: See Table 5-2 for details.

2: Bit D11 = '1' (while all other bits are "0") enables the device to output 0.5 * V_{DD} (= middle scale output).

TABLE 5-4: DAC REGISTER

Bit Name	C2	C1	C0	$RDY/\overline{BSY}$	POR	PD1	PD0	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
Bit Function	Command Type			(1)		Power-Down Select		Data (12 bits)											

Note 1: Write EEPROM status indication bit (0:EEPROM write is not completed. 1:EEPROM write is complete.)

5.5 Normal and Power-Down Modes

The device has two modes of operation: Normal mode and power-down mode. The mode is selected by programming the power-down bits (PD1 and PD0) in the Configuration register. The user can also program the two power-down bits in non-volatile EEPROM memory.

When the normal mode is selected, the device operates a normal digital-to-analog conversion. If the power-down mode is selected, the device enters a power saving condition by shutting down most of the internal circuits. During the power-down mode, all internal circuits except the I^2C interface are disabled and there is no data conversion event, and no V_{OUT} is available. The device also switches the output stage from the output of the amplifier to a known resistive load. The value of the resistive load is determined by the state of the power-down bits (PD1 and PD0). Table 5-2 shows the outcome of the power-down bit and the resistive load.

During the power-down mode, the device draws about 60 nA (typical). Although most of internal circuits are shutdown, the serial interface remains active in order to receive the I^2C command.

The device exits the power-down mode immediately when (a) it receives a new write command for normal mode or (b) it receives an I^2C General Call Wake-Up Command.

When the DAC operation mode is changed from power-down to normal mode, the output settling time takes less than 10 µs, but greater than the standard Active mode settling time (6 µs, typical).

TABLE 5-2: POWER-DOWN BITS

PD1	PD0	Function
0	0	Normal Mode
0	1	1 kΩ resistor to ground (1)
1	0	100 kΩ resistor to ground (1)
1	1	500 kΩ resistor to ground (1)

Note 1: In the power-down mode: V_{OUT} is off and most of internal circuits are disabled.

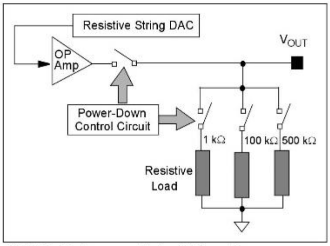


FIGURE 5-1: *Output Stage for Power-Down Mode.*

5.0 GENERAL DESCRIPTION

The MCP4725 is a single channel buffered voltage output 12-bit DAC with non-volatile memory (EEPROM). The user can store configuration register bits (2 bits) and DAC input data (12 bits) in non-volatile EEPROM (14 bits) memory.

When the device is powered on first, it loads the DAC code from the EEPROM and outputs the analog output accordingly with the programmed settings. The user can reprogram the EEPROM or DAC register any time.

The device uses a resistor string architecture. DAC's output is buffered with a low power precision amplifier. This output amplifier provides low offset voltage and low noise, as well as rail-to-rail output. The amplifier can also provide high source currents (V_{OUT} pin to V_{SS}).

The DAC can be configured to normal or power saving power-down mode by setting the configuration register bits.

The device uses a two-wire I^2C compatible serial interface and operates from a single power supply ranging from 2.7V to 5.5V.

5.1 Output Voltage

The input coding to the MCP4725 device is unsigned binary. The output voltage range is from 0V to V_{DD}. The output voltage is given in Equation 5-1:

EQUATION 5-1:

$$V_{OUT} = \frac{(V_{REF} \times D_n)}{4096}$$

Where:

V_{REF} = V_{DD}

D_n = Input code

5.1.1 OUTPUT AMPLIFIER

The DAC output is buffered with a low-power, precision CMOS amplifier. This amplifier provides low offset voltage and low noise. The output stage enables the device to operate with output voltages close to the power supply rails. Refer to **Section 1.0 "Electrical Characteristics"** for range and load conditions.

The output amplifier can drive the resistive and high capacitive loads without oscillation. The amplifier can provide maximum load current as high as 25 mA which is enough for most of a programmable voltage reference applications.

5.1.2 DRIVING RESISTIVE AND CAPACITIVE LOADS

The MCP4725 output stage is capable of driving loads up to 1000 pF in parallel with 5 kΩ load resistance. Figure 2-15 shows the V_{OUT} vs. Resistive Load. V_{OUT} drops slowly as the load resistance decreases after about 3.5 kΩ.

5.2 LSB SIZE

One LSB is defined as the ideal voltage difference between two successive codes. (see Equation 4-1). Table 5-1 shows an example of the LSB size over full-scale range (V_{DD}).

TABLE 5-1: LSB SIZES FOR MCP4725 (EXAMPLE)

Full-Scale Range (V_{DD})	LSB Size	Condition
3.0V	0.73 mV	3 / 4096
5.0V	1.22 mV	5 / 4096

5.3 Voltage Reference

The MCP4725 device uses the V_{DD} as its voltage reference. Any variation or noises on the V_{DD} line can affect directly on the DAC output. The V_{DD} needs to be as clean as possible for accurate DAC performance.

5.4 Reset Conditions

In the Reset conditions, the device uploads the EEPROM data into the DAC register. The device can be reset by two independent events: (a) by POR or (b) by I^2C General Call Reset Command.

The factory default settings for the EEPROM prior to shipment are shown in Table 4-3 (set for a middle scale output). The user can rewrite or read the DAC register or EEPROM anytime after the Power-On-Reset event.

5.4.1 POWER-ON-RESET

The device's internal Power-On-Reset (POR) circuit ensures that the device powers up in a defined state.

If the power supply voltage is less than the POR threshold (V_{POR} = 2V, typical), all circuits are disabled and there will be no DAC output. When the V_{DD} increases above the V_{POR}, the device takes a reset state. During the reset period, the device uploads all configuration and DAC input codes from EEPROM. The DAC output will be the same as for the value last stored in the EEPROM. This enables the device returns to the same state that it was at the last write to the EEPROM before it was powered off.

4.9 Offset Error Drift

Offset error drift is the variation in offset error due to a change in ambient temperature. The offset error drift is typically expressed in ppm/°C.

4.10 Settling Time

The Settling time is the time delay required for the DAC output to settle to its new output value from the start of code transition, within specified accuracy. In the MCP4725, the settling time is a measure of the time delay until the DAC output reaches its final value (within 0.5 LSB) when the DAC code changes from 400h to C00h.

4.11 Major-Code Transition Glitch

Major-code transition glitch is the impulse energy injected into the DAC analog output when the code in the DAC register changes state. It is normally specified as the area of the glitch in nV-Sec. and is measured when the digital code is changed by 1 LSB at the major carry transition (Example: 011...111 to 100... 000, or 100... 000 to 011 ... 111).

4.12 Digital Feedthrough

Digital feedthrough is the glitch that appears at the analog output caused by coupling from the digital input pins of the device. It is specified in nV-Sec. and is measured with a full scale change on the digital input pins (Example: 000... 000 to 111... 111, or 111... 111 to 000... 000). The digital feedthrough is measured when the DAC is not being written to the register.

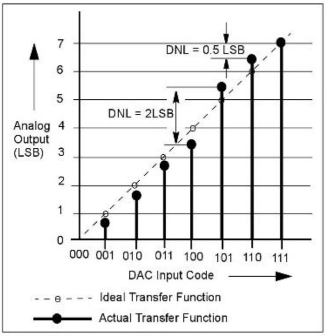


FIGURE 4-2: *DNL Accuracy.*

4.5 Offset Error

Offset error (Figure 4-3) is the deviation from zero voltage output when the digital input code is zero. This error affects all codes by the same amount. In the MCP4725, the offset error is not trimmed at the factory. However, it can be calibrated by software in application circuits.

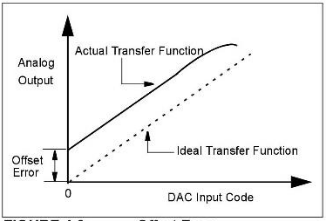


FIGURE 4-3: *Offset Error.*

4.6 Gain Error

Gain error (see Figure 4-4) is the difference between the actual full-scale output voltage from the ideal output voltage on the transfer curve. The gain error is calculated after nullifying the offset error, or full scale error minus the offset error.

The gain error indicates how well the slope of the actual transfer function matches the slope of the ideal transfer function. The gain error is usually expressed as percent of full-scale range (% of FSR) or in LSB.

In the MCP4725, the gain error is not calibrated at the factory and most of the gain error is contributed by the output op amp saturation near the code range beyond 4000. For the applications which need the gain error specification less than 1% maximum, the user may consider using the DAC code range between 100 and 4000 instead of using full code range (code 0 to 4095). The DAC output of the code range between 100 and 4000 is much linear than full-scale range (0 to 4095). The gain error can be calibrated by software in applications.

4.7 Full-Scale Error (FSE)

Full-scale error (Figure 4-4) is the sum of offset error plus gain error. It is the difference between the ideal and measured DAC output voltage with all bits set to one (DAC input code = FFFh).

EQUATION 4-4:

$$FSE = \frac{(V_{OUT} - V_{Ideal})}{LSB}$$

Where:

V_{Ideal} = $(V_{REF})(1 - 2^{-n}) - V_{OFFSET}$

V_{REF} = The reference voltage. $V_{REF} = V_{DD}$ in the MCP4725

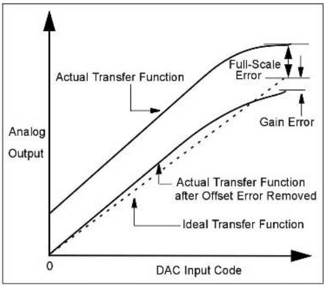


FIGURE 4-4: *Gain Error and Full-Scale Error.*

4.8 Gain Error Drift

Gain error drift is the variation in gain error due to a change in ambient temperature. The gain error drift is typically expressed in ppm/°C.

3.0 PIN DESCRIPTIONS

The descriptions of the pins are listed in Table 3-1.

TABLE 3-1: PIN FUNCTION TABLE

Pin No. SOT-23	Name	Function
1	V_{OUT}	Analog Output Voltage
2	V_{SS}	Ground Reference
3	V_{DD}	Supply Voltage
4	SDA	I^2C Serial Data
5	SCL	I^2C Serial Clock Input
6	A0	Device Address Selection pin. This pin can be tied to V_{SS} or V_{DD}, or can be actively driven by the digital logic levels. The logic state of this pin determines what the A0 bit of the I^2C address bits should be.

3.1 Analog Output Voltage (V_{OUT})

V_{OUT} is an analog output voltage from the DAC device. DAC output amplifier drives this pin with a range of V_{SS} to V_{DD}.

3.2 Supply Voltage (V_{DD}, V_{SS})

V_{DD} is the power supply pin for the device. The voltage at the V_{DD} pin is used as the supply input as well as the DAC reference input. The power supply at the V_{DD} pin should be clean as possible for a good DAC performance.

This pin requires an appropriate bypass capacitor of about 0.1 µF (ceramic) to ground. An additional 10 µF capacitor (tantalum) in parallel is also recommended to further attenuate high frequency noise present in application boards. The supply voltage (V_{DD}) must be maintained in the 2.7V to 5.5V range for specified operation.

V_{SS} is the ground pin and the current return path of the device. The user must connect the V_{SS} pin to a ground plane through a low impedance connection. If an analog ground path is available in the application PCB (printed circuit board), it is highly recommended that the V_{SS} pin be tied to the analog ground path or isolated within an analog ground plane of the circuit board.

3.3 Serial Data Pin (SDA)

SDA is the serial data pin of the I^2C interface. The SDA pin is used to write or read the DAC register and EEPROM data. The SDA pin is an open-drain N-chan nel driver. Therefore, it needs a pull-up resistor from the V_{DD} line to the SDA pin. Except for start and stop conditions, the data on the SDA pin must be stable during the high period of the clock. The high or low state of the SDA pin can only change when the clock signal on the SCL pin is low. Refer to **Section 7.0 "I^2C Serial Interface Communication"** for more details of I^2C Serial Interface communication.

3.4 Serial Clock Pin (SCL)

SCL is the serial clock pin of the I^2C interface. The MCP4725 acts only as a slave and the SCL pin accepts only external serial clocks. The input data from the Master device is shifted into the SDA pin on the rising edges of the SCL clock and output from the MCP4725 occurs at the falling edges of the SCL clock. The SCL pin is an open-drain N-channel driver. Therefore, it needs a pull-up resistor from the V_{DD} line to the SCL pin. Refer to **Section 7.0 "I^2C Serial Interface Communication"** for more details of I^2C Serial Interface communication.

3.5 Device Address Selection Pin (A0)

This pin is used to select the A0 address bit by the user. The user can tie this pin to V_{SS} (logic '0'), or V_{DD} (logic '1'), or can be actively driven by the digital logic levels, such as the I^2C Master Output. See **Section 7.2 "Device Addressing"** for more details of the address bits.

Note: Unless otherwise indicated, T_A = +25°C, V_{DD} = +5.0V, V_{SS} = 0V, R_L = 5 kΩ to V_{SS}, C_L = 100 pF.

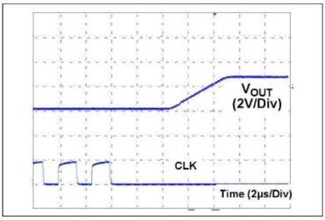


FIGURE 2-24: *Exiting Power Down Mode.*

Note: Unless otherwise indicated, T_A = +25°C, V_{DD} = +5.0V, V_{SS} = 0V, R_L = 5 kΩ to V_{SS}, C_L = 100 pF.

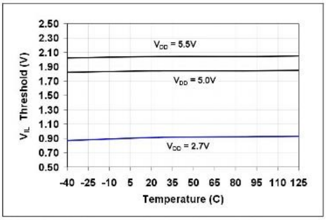


FIGURE 2-18: *V_{IN} Low Threshold vs. Temperature and V_{DD}.*

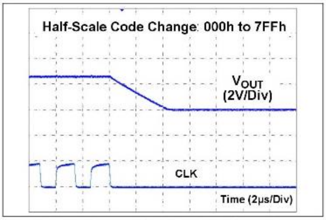


FIGURE 2-21: *Half-Scale Settling Time.*

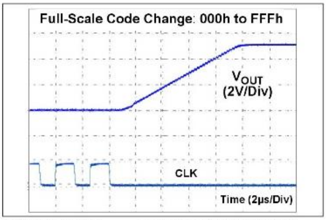


FIGURE 2-19: *Full-Scale Settling Time.*

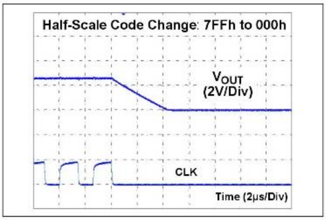


FIGURE 2-22: *Half-Scale Settling Time.*

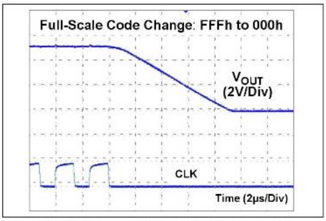


FIGURE 2-20: *Full-Scale Settling Time.*

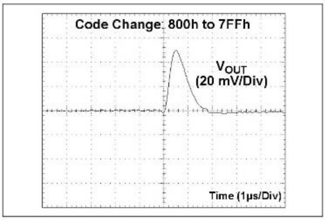


FIGURE 2-23: *Code Change Glitch.*

Note: Unless otherwise indicated, T_A = +25°C, V_{DD} = +5.0V, V_{SS} = 0V, R_L = 5 kΩ to V_{SS}, C_L = 100 pF.

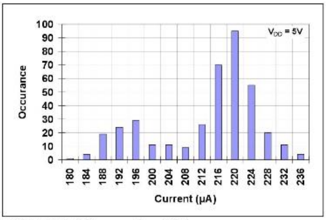


FIGURE 2-12: *I_{DD} Histogram .*

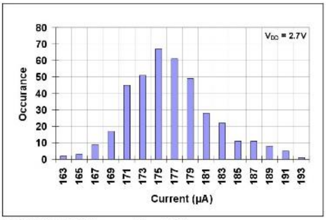


FIGURE 2-13: *I_{DD} Histogram.*

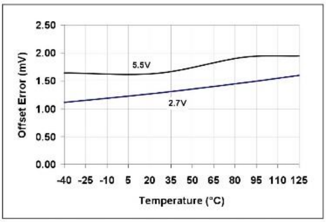


FIGURE 2-14: *Offset Error vs. Temperature and V_{DD}.*

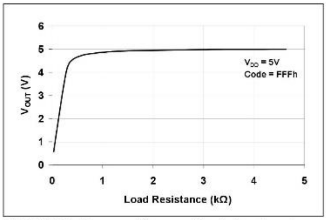


FIGURE 2-15: *V_{OUT} vs. Resistive Load.*

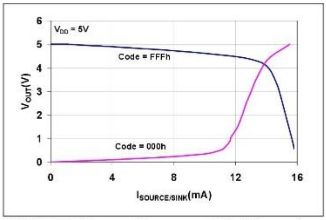


FIGURE 2-16: *Source and Sink Current Capability.*

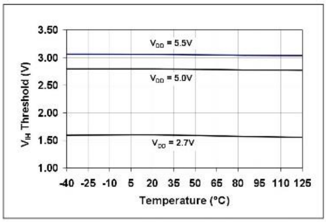


FIGURE 2-17: *V_{IN} High Threshold vs. Temperature and V_{DD}.*

Note: Unless otherwise indicated, $T_A = +25°C$, $V_{DD} = +5.0V$, $V_{SS} = 0V$, $R_L = 5\ k\Omega$ to V_{SS}, $C_L = 100\ pF$.

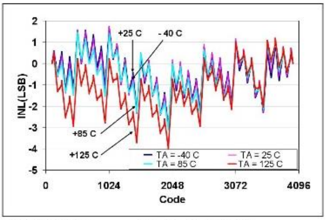


FIGURE 2-7: *INL vs. Code and Temperature (V_{DD} = 2.7V).*

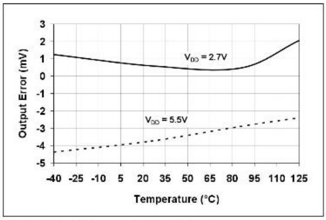


FIGURE 2-10: *Output Error vs. Temperature (Code = 4000d).*

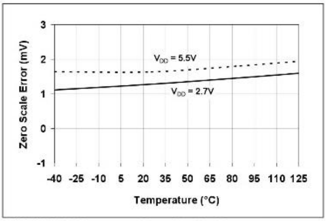


FIGURE 2-8: *Zero Scale Error vs. Temperature (Code = 000d).*

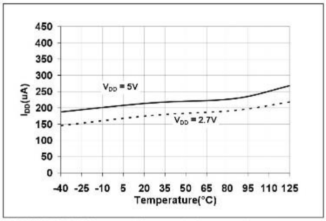


FIGURE 2-11: *I_{DD} vs. Temperature.*

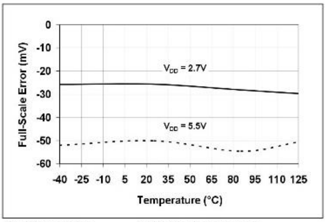


FIGURE 2-9: *Full-Scale Error vs. Temperature (Code = 4095d).*

2.0 TYPICAL PERFORMANCE CURVES

Note:	The graphs and tables provided following this note are a statistical summary based on a limited number of samples and are provided for informational purposes only. The performance characteristics listed herein are not tested or guaranteed. In some graphs or tables, the data presented may be outside the specified operating range (e.g., outside specified power supply range) and therefore, outside the warranted range.

Note: Unless otherwise indicated, T_A = +25°C, V_{DD} = +5.0V, V_{SS} = 0V, R_L = 5 kΩ to V_{SS}, C_L = 100 pF.

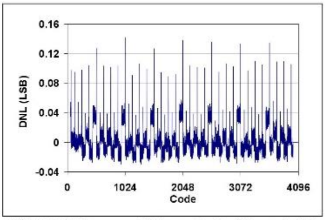


FIGURE 2-1: *DNL vs. Code (V_{DD} = 5.5V).*

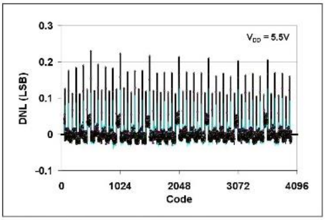


FIGURE 2-2: *DNL vs. Code and Temperature (TA = -40°C to +125°C).*

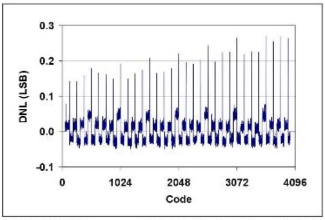


FIGURE 2-3: *DNL vs. Code (V_{DD} = 2.7V).*

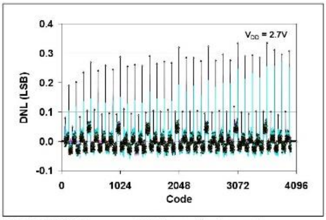


FIGURE 2-4: *DNL vs. Code and Temperature (T_A = -40°C to +125°C).*

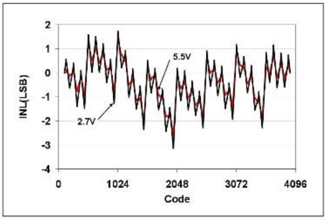


FIGURE 2-5: *INL vs. Code.*

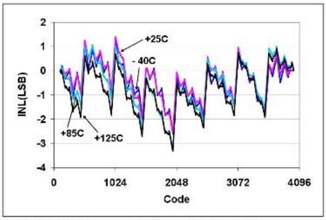


FIGURE 2-6: *INL vs. Code and Temperature (V_{DD} = 5.5V).*

TEMPERATURE CHARACTERISTICS

Electrical Specifications: Unless otherwise indicated, V_{DD} = +2.7V to +5.5V, V_{SS} = GND.						
Parameters	**Sym**	**Min**	**Typ**	**Max**	**Units**	**Conditions**
Temperature Ranges						
Specified Temperature Range	T_A	-40	—	+125	°C	
Operating Temperature Range	T_A	-40	—	+125	°C	
Storage Temperature Range	T_A	-65	—	+150	°C	
Thermal Package Resistances						
Thermal Resistance, 6L-SOT-23	θ_{JA}	—	190	—	°C/W	

ELECTRICAL CHARACTERISTICS (CONTINUED)

Electrical Specifications: Unless otherwise indicated, all parameters apply at V_{DD} = + 2.7V to 5.5V, V_{SS} = 0V, R_L = 5 kΩ from V_{OUT} to V_{SS}, C_L = 100 pF, T_A = -40°C to +125°C. Typical values are at +25°C.

Parameter	Sym	Min	Typ	Max	Units	Conditions
Power Up Time	T_{PU}	—	2.5	—	µs	V_{DD} = 5V
		—	5	—	µs	V_{DD} = 3V Coming out of Power-down mode, started from falling edge of ACK pulse in I^2C command.
DC Output Impedance	R_{OUT}	—	1	—	Ω	Normal mode (V_{OUT} to V_{SS})
		—	1	—	kΩ	Power-Down Mode 1 (V_{OUT} to V_{SS})
		—	100	—	kΩ	Power-Down Mode 2 (V_{OUT} to V_{SS})
		—	500	—	kΩ	Power-Down Mode 3 (V_{OUT} to V_{SS})
Dynamic Performance						
Major Code Transition Glitch		—	45	—	nV-s	1 LSB change around major carry (800h to 7FFh) (**Note 2**)
Digital Feedthrough		—	<10	—	nV-s	**Note 2**
Digital Interface						
Output Low Voltage	V_{OL}	—	—	0.4	V	I_{OL} = 3 mA
Input High Voltage (SDA and SCL Pins)	V_{IH}	$0.7V_{DD}$	—	—	V	
Input Low Voltage (SDA and SCL Pins)	V_{IL}	—	—	$0.3V_{DD}$	V	
Input High Voltage (A0 Pin)	V_{A0-Hi}	$0.8V_{DD}$	—	—		**Note 4**
Input Low Voltage (A0 Pin)	V_{A0-IL}	—	—	$0.2V_{DD}$		**Note 4**
Input Leakage	I_{LI}	—	—	±1	µA	SCL = SDA = A0 = V_{SS} or SCL = SDA = A0 = V_{DD}
Pin Capacitance	C_{PIN}	—	—	3	pF	**Note 2**
EEPROM						
EEPROM Write Time	TWRITE	—	25	50	ms	EEPROM Write time for 14 bits
Data Retention		—	200	—	Years	At +25°C, **(Note 2)**
Endurance		1	—	—	Million Cycles	At +25°C, **(Note 2)**

Note 1: Test Code Range: 100 to 4000.
2: This parameter is ensure by design and not 100% tested.
3: Within 1/2 LSB of the final value when code changes from 1/4 to 3/4 (400h to C00h) of full-scale.
4: Logic state of external address pin (A0 pin).

1.0 ELECTRICAL CHARACTERISTICS

Absolute Maximum Ratings†

V_{DD} 6.5V
All inputs and outputs w.r.t V_{SS} .... –0.3V to V_{DD}+0.3V
Current at Input Pins .... ±2 mA
Current at Supply Pins .... ±50 mA
Current at Output Pins .... ±25 mA
Storage Temperature .... -65°C to +150°C
Ambient Temp. with Power Applied .... -55°C to +125°C
ESD protection on all pins .... ≥ 6 kV HBM, ≥ 400V MM
Maximum Junction Temperature (T_J) .... +150°C

† Notice: Stresses above those listed under "Maximum ratings" may cause permanent damage to the device. This is a stress rating only and functional operation of the device at these or any other conditions above those indicated in the operation listings of this specification is not implied. Exposure to maximum rating conditions for extended periods may affect device reliability

ELECTRICAL CHARACTERISTICS

Electrical Specifications: Unless otherwise indicated, all parameters apply at V_{DD} = + 2.7V to 5.5V, V_{SS} = 0V, R_L = 5 kΩ from V_{OUT} to V_{SS}, C_L = 100 pF, T_A = -40°C to +125°C. Typical values are at +25°C.

Parameter	Sym	Min	Typ	Max	Units	Conditions
Power Requirements						
Operating Voltage	V_{DD}	2.7		5.5	V	
Supply Current	I_D	—	210	400	µA	Digital input grounded, output unloaded, code = 000h
Power-Down Current	I_{DDP}	—	0.06	2.0	µA	V_{DD} = 5.5V
Power-On-Reset Threshold	V_{POR}	—	2	—	V	
DC Accuracy						
Resolution	n	12	—	—	Bits	Code Range = 000h to FFFh
INL Error	INL	—	±2	±14.5	LSB	**Note 1**
DNL	DNL	-0.75	±0.2	±0.75	LSB	**Note 1**
Offset Error	V_{OS}		0.02	0.75	% of FSR	Code = 000h
Offset Error Drift	ΔV_{OS}/°C	—	±1	—	ppm/°C	-45°C to +25°C
		—	±2	—	ppm/°C	+25°C to +85°C
Gain Error	G_E	-2	-0.1	2	% of FSR	Code FFFh, not including offset error
Gain Error Drift	ΔG_E/°C	—	-3	—	ppm/°C	
Output Amplifier						
Phase Margin	p_M	—	66	—	Degree(°)	C_L = 400 pF, R_L = ∞
Capacitive Load Stability	C_L	—	—	1000	pF	R_L = 5 kΩ, **Note 2**
Slew Rate	SR	—	0.55	—	V/µs	
Short Circuit Current	I_{SC}	—	15	24	mA	V_{DD} = 5V, V_{OUT} = Grounded
Output Voltage Settling Time	T_S	—	6	—	µs	**Note 3**

Note 1: Test Code Range: 100 to 4000.
2: This parameter is ensure by design and not 100% tested.
3: Within 1/2 LSB of the final value when code changes from 1/4 to 3/4 (400h to C00h) of full-scale.
4: Logic state of external address pin (A0 pin).

B. Datasheet OP-AMP JFET LF356

Product Folder | Sample & Buy | Technical Documents | Tools & Software | Support & Community

TEXAS INSTRUMENTS

LF155, LF156, LF256, LF257
LF355, LF356, LF357

SNOSBH0D – MAY 2000 – REVISED NOVEMBER 2015

LFx5x JFET Input Operational Amplifiers

1 Features

- Advantages
  - Replace Expensive Hybrid and Module FET Op Amps
  - Rugged JFETs Allow Blow-Out Free Handling Compared With MOSFET Input Devices
  - Excellent for Low Noise Applications Using Either High or Low Source Impedance—Very Low 1/f Corner
  - Offset Adjust Does Not Degrade Drift or Common-Mode Rejection as In Most Monolithic Amplifiers
  - New Output Stage Allows Use of Large Capacitive Loads (5,000 pF) Without Stability Problems
  - Internal Compensation and Large Differential Input Voltage Capability
- Common Features
  - Low Input Bias Current: 30 pA
  - Low Input Offset Current: 3 pA
  - High Input Impedance: 10^{12} Ω
  - Low Input Noise Current: 0.01 pA/$\sqrt{Hz}$
  - High Common-Mode Rejection Ratio: 100 dB
  - Large DC Voltage Gain: 106 dB
- Uncommon Features
  - Extremely Fast Settling Time to 0.01%:
    - 4 µs for the LFx55 devices
    - 1.5 µs for the LFx56
    - 1.5 µs for the LFx57 (A_V = 5)
  - Fast Slew Rate:
    - 5 V/µs for the LFx55
    - 12 V/µs for the LFx56
    - 50 V/µs for the LFx57 (A_V = 5)
  - Wide Gain Bandwidth:
    - 2.5 MHz for the LFx55 devices
    - 5 MHz for the LFx56
    - 20 MHz for the LFx57 (A_V = 5)
  - Low Input Noise Voltage:
    - 20 nV/$\sqrt{Hz}$ for the LFx55
    - 12 nV/$\sqrt{Hz}$ for the LFx56
    - 12 nV/$\sqrt{Hz}$ for the LFx57 (A_V = 5)

2 Applications

- Precision High-Speed Integrators
- Fast D/A and A/D Converters
- High Impedance Buffers
- Wideband, Low Noise, Low Drift Amplifiers
- Logarithmic Amplifiers
- Photocell Amplifiers
- Sample and Hold Circuits

3 Description

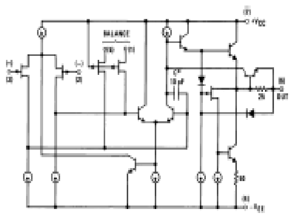
The LFx5x devices are the first monolithic JFET input operational amplifiers to incorporate well-matched, high-voltage JFETs on the same chip with standard bipolar transistors (BI-FET™ Technology). These amplifiers feature low input bias and offset currents/low offset voltage and offset voltage drift, coupled with offset adjust, which does not degrade drift or common-mode rejection. The devices are also designed for high slew rate, wide bandwidth, extremely fast settling time, low voltage and current noise and a low 1/f noise corner.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
LFx5x	SOIC (8)	4.90 mm × 3.91 mm
	TO-CAN (8)	9.08 mm × 9.08 mm
	PDIP (8)	9.81 mm × 6.35 mm

(1) For all available packages, see the orderable addendum at the end of the data sheet.

Simplified Schematic

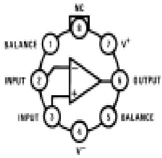


3 pF in LF357 series

An IMPORTANT NOTICE at the end of this data sheet addresses availability, warranty, changes, use in safety-critical applications, intellectual property matters and other important disclaimers. PRODUCTION DATA.

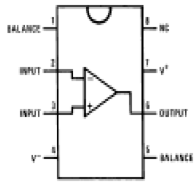
5 Pin Configuration and Functions

LMC Package
8-Pin TO-99
Top View



Available per JM38510/11401 or JM38510/11402

D or P Package
8-Pin SOIC or PDIP
Top View



Pin Functions

PIN		I/O	DESCRIPTION
NAME	NO.		
BALANCE	1, 5	I	Balance for input offset voltage
+INPUT	3	I	Noninverting input
–INPUT	2	I	Inverting input
NC	8	—	No connection
OUTPUT	6	O	Output
V+	7	—	Positive power supply
V–	4	—	Negative power supply

6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted) [1][2][3]

				MIN	MAX	UNIT
Supply voltage		LF155x, LF256x, LF356B			±22	V
		LF35x			±18	
Differential input voltage		LF15x, LF25x, LF356B			±40	V
		LF35x			±30	
Input voltage [4]		LF15x, LF25x, LF356B			±20	V
		LF35x			±16	
Output short circuit duration				Continuous		—
T_{JMAX}		LMC package	LF15x		150	°C
			LF25x, LF356B, LF35x		115	
		P package	LF25x, LF356B, LF35x		100	
		D package	LF25x, LF356B, LF35x		100	
Soldering information (lead temp.)	TO-99 package	Soldering (10 sec.)			300	°C
	PDIP package	Soldering (10 sec.)			260	
	SOIC package	Vapor phase (60 sec.)	LF25x, LF356B, LF35x		215	
		Infrared (15 sec.)	LF25x, LF356B, LF35x		220	
Storage temperature, T_{stg}				−65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) The maximum power dissipation for these devices must be derated at elevated temperatures and is dictated by T_{JMAX}, θ_{JA}, and the ambient temperature, T_A. The maximum available power dissipation at any temperature is $P_D = (T_{JMAX} - T_A) / \theta_{JA}$ or the 25°C P_{dMAX}, whichever is less.
(3) If Military/Aerospace specified devices are required, contact the TI Sales Office/Distributors for availability and specifications.
(4) Unless otherwise specified the absolute maximum negative input voltage is equal to the negative power supply voltage.

6.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human body model (HBM), per ANSI/ESDA/JEDEC JS-001 [1][2]	±1000	V

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
(2) 100 pF discharged through 1.5-kΩ resistor

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

		MIN	NOM	MAX	UNIT
Supply voltage, V_S	LF15x	±15	V_S	±20	V
	LF25x	±15	V_S	±20	
	LF356B	±15	V_S	±20	
	LF35x			±15	
T_A	LF15x	–55	T_A	125	°C
	LF25x	–25	T_A	85	
	LF356B	0	T_A	70	
	LF35x	0	T_A	70	

6.6 DC Electrical Characteristics, $T_A = T_J = 25°C$, $V_S = ±15$ V

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
Supply current	LF155		2	4	mA
	LF355		2	4	
	LFx56, LF356B		5	7	
	LF356		5	10	
	LF357		5	10	

6.7 DC Electrical Characteristics

See [1]

PARAMETER		TEST CONDITIONS			MIN	TYP	MAX	UNIT
V_{OS}	Input offset voltage	$R_S = 50\ \Omega$	$T_A = 25°C$	LF15x, LF25x, LF356B		3	5	mV
				LF35x		3	10	
			Over temperature	LF15x			7	
				LF25x, LF356B			6.5	
				LF35x			13	
$\Delta V_{OS}/\Delta T$	Average TC of input offset voltage	$R_S = 50\ \Omega$		LF15x, LF25x, LF356B, LF35x		5		μV/°C
$\Delta TC/\Delta V_{OS}$	Change in average TC with V_{OS} adjust	$R_S = 50\ \Omega$[2]		LF15x, LF25x, LF356B, LF35x		0.5		μV/°C per mV
I_{OS}	Input offset current	$T_J = 25°C$[1] [3]		LF15x, LF25x, LF356B		3	20	pA
				LF35x		3	50	
		$T_J \le T_{HIGH}$		LF15x			20	nA
				LF25x, LF356B			1	
				LF35x			2	
I_B	Input bias current	$T_J = 25°C$[1] [3]		LF15x, LF25x, LF356B		30	100	pA
				LF35x		30	200	
		$T_J \le T_{HIGH}$		LF15x			50	nA
				LF25x, LF356B			5	
				LF35x			8	
R_{IN}	Input resistance	$T_J = 25°C$		LF15x, LF25x, LF356B, LF35x		10^{12}		Ω
A_{VOL}	Large signal voltage gain	$V_S = ±15$ V, $V_O = ±10$ V, $R_L = 2\ k\Omega$	$T_A = 25°C$	LF15x, LF25x, LF356B	50	200		V/mV
				LF35x	25	200		
			Over temperature	LF15x, LF25x, LF356B	25			
				LF35x	15			
V_O	Output voltage swing	$V_S = ±15$ V, $R_L = 10\ k\Omega$		LF15x, LF25x, LF356B, LF35x	±12	±13		V
		$V_S = ±15$ V, $R_L = 2\ k\Omega$		LF15x, LF25x, LF356B, LF35x	±10	±12		

(1) Unless otherwise stated, these test conditions apply:

	LF15x	LF25x	LF356B	LF35x
Supply Voltage, V_S	$±15\ V \le V_S \le ±20$ V	$±15\ V \le V_S \le ±20$ V	$±15\ V \le V_S \le ±20$ V	$V_S = ±15$ V
T_A	$-55°C \le T_A \le +125°C$	$-25°C \le T_A \le +85°C$	$0°C \le T_A \le +70°C$	$0°C \le T_A \le +70°C$
T_{HIGH}	+125°C	+85°C	+70°C	+70°C

and V_{OS}, I_B and I_{OS} are measured at $V_{CM} = 0$.

(2) The Temperature Coefficient of the adjusted input offset voltage changes only a small amount (0.5 μV/°C typically) for each mV of adjustment from its original unadjusted value. Common-mode rejection and open-loop voltage gain are also unaffected by offset adjustment.

(3) The input bias currents are junction leakage currents which approximately double for every 10°C increase in the junction temperature, T_J. Due to limited production test time, the input bias currents measured are correlated to junction temperature. In normal operation the junction temperature rises above the ambient temperature as a result of internal power dissipation, Pd. $T_J = T_A + \theta_{JA}$ Pd where θ_{JA} is the thermal resistance from junction to ambient. Use of a heat sink is recommended if input bias current is to be kept to a minimum.

9 Power Supply Recommendations

See the *Recommended Operating Conditions* for the minimum and maximum values for the supply input voltage and operating junction temperature.

10 Layout

10.1 Layout Guidelines

10.1.1 Printed-Circuit-Board Layout For High-Impedance Work

It is generally recognized that any circuit which must operate with less than 1000 pA of leakage current requires special layout of the PCB. When one wishes to take advantage of the low input bias current of the LFx5x, typically less than 30 pA, it is essential to have an excellent layout. Fortunately, the techniques of obtaining low leakages are quite simple. First, the user must not ignore the surface leakage of the PCB, even though it may sometimes appear acceptably low, because under conditions of high humidity or dust or contamination, the surface leakage will be appreciable.

To minimize the effect of any surface leakage, lay out a ring of foil completely surrounding the inputs of the LFx5x and the terminals of capacitors, diodes, conductors, resistors, relay terminals, and so forth, connected to the inputs of the op amp, as in Figure 62. To have a significant effect, guard rings must be placed on both the top and bottom of the PCB. This PC foil must then be connected to a voltage that is at the same voltage as the amplifier inputs, because no leakage current can flow between two points at the same potential. For example, a PCB trace-to-pad resistance of 10 TΩ, which is normally considered a very large resistance, could leak 5 pA if the trace were a 5-V bus adjacent to the pad of the input. If a guard ring is used and held close to the potential of the amplifier inputs, it will significantly reduce this leakage current.

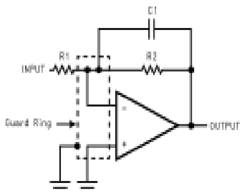


Figure 58. Inverting Amplifier

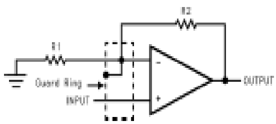


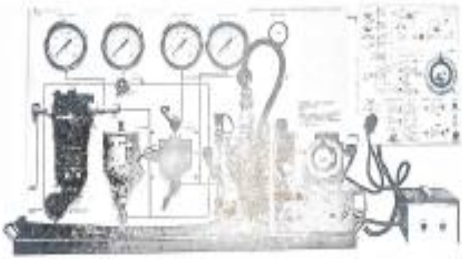
Figure 59. Noninverting Amplifier

C. ***Buku Datasheet Elektro Hidrolik Servomechanism EHS160***

Leaflet E160

FEEDBACK

ELECTRO-HYDRAULIC SERVO EHS 160



Hydraulic power control constitutes the most common form of precise power manipulation used in modern technology. It is used throughout aircraft, ships, machine tools, and in every industry employing automatic controls up to many hundreds of horsepower.

The EHS160, specifically designed for teaching technicians and student engineers, embodies the latest hydraulic components and electronic circuits in a comprehensive system. Due care has been taken to fit the demonstrations and experimental work to the ultimate requirements of the student.

The apparatus and its ancillary transducers and electronics reproduce exactly the conditions found in industrial installations.

Features

- ☐ Complete with all transducers including line pressure, line flow, line force
- ☐ Includes rotary motor and linear actuator as output alternatives
- ☐ Calibrated output loading facility
- ☐ 400Hz synchro on a.c. error channel
- ☐ Linear d.c. displacement control on linear actuator
- ☐ Electronic unit complete with all power supplies
- ☐ Standard industrial hydraulic components used throughout
- ☐ Hydraulic power supply available if required, type HPS161.
- ☐ Clear mimic diagrams show hydraulic and electrical connecting lines.

Demonstrations & Experiments

STEADY STATE PERFORMANCE

Electro-hydraulic valve, motor and cylinder characteristics. Flow gauge calibration. Use of other hydraulic components, electronic amplifiers and error channels. Characteristics of rotary velocity, rotary position and linear position servos - velocity and position errors and stiffness, return difference, servo types 0, 1 and 2, error coefficient, position feedback.

TIME DEPENDENT PERFORMANCE

Methods of representing time dependence - differential equation, frequency response, Bode plot, Nyquist plot, transient response, Laplace transform, pole-zero plot. Basic forms of time dependence - simple and resonant lag, integration, differentiation, transport lag.

Performance of practical servo components.
Servo valve frequency response.
Valve/motor combined frequency response.
Rotary velocity, rotary position and linear position servos - damping factor, effect of inertia, load spring, increased stiffness, stability, effect of transport lag.
Additional servo configurations - pressure, flow, force and digital position feedback.

By using Feedback LOGIKIT with Shaft Encoder SE256 or INTIKIT with Shaft Encoder SE266, the system may be controlled digitally.

Specification

Servo unit

Rotary hydraulic axial piston motor capable of 1500rev/min, 6.3 Newton-metres (4lbf ft) torque.

Linear hydraulic motor, 50mm (2in) stroke, double-acting, low friction type.

Hydraulic servo valve, high frequency, 4-port (usable as 3-port) electrically operated spool type.

Hydraulic pressure line filter, replacement element type.

Hydraulic accumulator, bag type, 0.37 litre ($22in^3$) volume.

Gauges 100mm (4in) Bourdon tube type, read [illegible] (input) values and protected from excessive vibration – for supply line pressure and flow, servo valve outport.

Flow gauge 0.1150 [illegible] ([illegible]).

Relief and replenishing valve protects motors etc from pressures above 100 bar (1500lbf/in^2) and from cavitation.

Relief valve, [illegible] ([illegible]lbf/in^2) protects flow gauge.

Pressure transducers (2) measure dynamically the servo valve output pressures.

Flow transducer measures dynamically the flow monitored by flow gauge.

Force transducer measures dynamically force applied by the cylinder.

Oil temperature gauge.

Coupling, quick-connect self-sealing, allows either rotary or linear motor to be driven.

Coulomb friction brake and torque meter – pressure applied or removed rapidly.

Inertial loads, two sizes.

Rotary transducer comprises d.c. tacho-generator and 400Hz synchro transformer.

Linear transducer comprises d.c. linear velocity transducer and linear potentiometer.

Transport bag/case, 3 metres (120in).

NOTE: Instruments indicating pressure and torque have scales in SI units. If scales are to be in British units (lb and in) this must be specified on the order.

Control Unit

Constructed for use also as a self-standing unit, the control panel is clipped to the side of the servo unit. It comprises all the electronics to provide these facilities:

Rotary and linear reference position settings.
400Hz supply for synchro transmitter.
Operational amplifier with summing resistors, variable attenuators, and selectable feedback configurations.
Servo valve drive amplifier with polarity and offset control.
Amplification for pressure, flow and force transducer outputs.
Supply for pressure, flow and force transducers, ±15V d.c.
Patch sockets to give maximum flexibility of configuration with minimum patch cords. All sockets are short-circuit proof.
All signals are of sufficient amplitude for direct viewing on general-purpose oscilloscope.

Electronic power unit

A small free-standing unit which provides the necessary +15V and –15V d.c. to the control unit. Its output is current-limited. It requires 200-250V, 50Hz or 100-130V 60Hz at less than 1 amp.

Hydraulic power supply, type HPS161 (optional)

The unit is fitted with anti-vibration mountings on a frame with castors.

This provides a maximum of 0.113 litre/sec ([illegible]) at 70 bar (1000lbf/in^2).

Pump drive motor is 220/240V, 11A, 50Hz single phase. Other voltages to special order.

Pump is submerged type mounted in 50 litre (10 gal) tank.

Water-cooled heat exchanger.

Because of legal restrictions on the transport of hydraulic oil, this is not supplied. A range of suitable oils is given in the handbook.

Ancillary equipment

Comprehensive instruction manual covering theory and practice of all experiments, patch cords, set of spanners.

The following equipment should be made available for use with the EHS160:-

L.F. test waveform generator such as the Feedback TWG300 or TWG301, and a general-purpose dual trace oscilloscope (long persistence, preferably).

Dimensions & Weights

	Width	Depth	Height	Weight
Servo unit	1000mm	380mm	610mm	47.6kg
	39.5in	15in	24in	105lb
Control panel	310mm	76mm	360mm	3.4kg
	12.25in	3.0in	14.50in	7.5lb
Electrical P.S.	140mm	290mm	130mm	5.1kg
	5.50in	11.50in	5in	11.3lb
Hydraulic P.S.	590mm	577mm	770mm	73kg
	23.25in	22.75in	30.5in	158lb
				(empty)

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FEEDBACK INSTRUMENTS LIMITED
PARK ROAD CROWBOROUGH SUSSEX TN6 2QR
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Subsidiary of FEEDBACK Ltd
TELEPHONE CROWBOROUGH [illegible]   CABLES FEEDBACK CROWBOROUGH [illegible]   TELEX [illegible]

On receipt of the equipment carry out the following checks and setting-up procedure:

Unpack the equipment. Check that the following items are present:

Servo unit with brake drum and large inertia disc attached, Force transducer and coupling, Flow transducer and two Pressure transducers.

Control unit
Electronic power unit
Rotary transducer assembly
Linear transducer assembly
Transport lag hose
High pressure supply hose
Return hose (clear)
Small inertia disc
Cylinder guard
Patch leads (nine, various lengths)
Tools (six Spanners, one Allen key)
Spare seals (eight, various sizes)
Hexagon plugs (four 1/4" BSP)
Hexagon nuts (5/8" BSP)

160H-11-2

and, if it has been ordered, the:

Hydraulic power unit HSP161

Thoroughly inspect all items for damage. If any item is damaged or any of the above items are missing, inform both the carrier and FEEDBACK INSTRUMENTS LTD immediately.

Stand the servo unit on a flat, rigid surface that is horizontal to within 1°. Attach the control unit to the servo unit by engaging the sprung pins with the keyhole slot.

Stand the electronic power unit beside the servo. Set the voltage selector to the appropriate position. If the supply voltage is intermediate between any of the available positions, use the next highest position.

Fill the hydraulic power unit with new, clean oil - approximately 10 Imp gal (45 litre). Suitable oils are Shell Tellus 27, BP Energol HLP65, Esso Nuto H44, Chevron EP Hydraulic Oil 9 and Caltex Rando HD-A.

If HSP161 power unit is supplied:

Remove the dust caps from the supply and return hoses, and from the HSP161 ports. Attach the hoses, using the sealing washers provided, and tighten adequately.

The purpose of this section is to indicate the correct operation of the equipment where it is not obvious by inspection.

5.1. Safety

It is important to note that large hydraulic pressures and mechanical forces are developed in the equipment. These can be dangerous if the equipment is treated carelessly.

Also note that the oil is flammable, having a closed flash point of 205°C (Shell Tellus 27).

In particular the warning on the servo unit panel must be observed scrupulously. This is:

WARNING – SUPPLY PRESSURE MUST BE ZERO

WHILE

* LINEAR TRANSDUCER IS UNGUARDED
* ATTACHING OR DETACHING FORCE TRANSDUCER, HYDRAULIC COUPLINGS OR BRAKE DRUM.

16091-13-1

5.2 Quick-connect couplings

The hydraulic couplings are released by pulling back the knurled collar on the female half. As the coupling separates, poppet valves automatically seal each half. This is always accompanied by a small amount of spillage, and it is advisable to hold a mopping cloth under the coupling when disconnecting it.

To connect the couplings, the collar must again be pulled back. The couplings should then be pushed together firmly and the collar released.

Note that the quick-connect coupling from the servo unit to the return hose contains no poppet valves and does not seal when disconnected. This is to prevent any accidental obstruction of the return flow which would over-stress the low pressure side of the system. To avoid spillage when the return hose is disconnected drain the return hose, including that on the servo unit, before disconnecting. To drain the hose, unscrew the large horizontal knurled knob located behind the servo unit panel immediately below the return flow gauge. Two or three turns are all that are necessary to admit air and allow drainage. Do not forget to retighten, by hand, firmly.

Always ensure that the mating surfaces of the couplings are clean before they are connected. Clean with a lint-free cloth. Dust caps are provided to protect the couplings when not in use.

5.3 Brake

To remove the brake pads from the drum, loosen the knurled knob at the front. Unscrew and slide out the pivot pin joining the front pad caliper to the brake arm.

Remove the front caliper. If the equipment is to be used before the brake is re-applied, tighten the knurled knob and swing the arm behind the panel to engage with the magnetic retainer.

To apply the brake pads to the drum, pull the brake arm forward until the rear pad touches the drum. Loosen the knurled knob sufficiently to allow the front pad caliper to engage behind the six domed Belleville washers. (These washers are stacked in alternate directions, bellows fashion, with concave ends.) Slide in and screw home the pivot pin. The brake can then be applied to any degree by tightening the knurled knob.

When the brake is to be used for any period the large inertia disc should be attached to assist heat dissipation.

The brake drum locates on the tapered motor shaft. To remove the drum, rotate the nut counter-clockwise to break the grip of the drum on the taper. If necessary, use the brake pads to lock the drum. As soon as the grip is broken, remove the pads to allow the drum to be removed.

To attach the drum, push it on to the shaft and rotate the nut clockwise to engage the thread. Continue rotating the nut until the drum has fully engaged on the taper, then finally tighten the nut with a spanner.

5.4 Inertia discs

Two inertia discs are provided. Either one of these may be attached to the left-hand side of the brake drum with the three screws provided. These screws must be tightened securely.

5.5 Flow gauge

1401-14-1

When the gauge is not in use, the ORIFICE CALIBRATOR should be left fully clockwise (open). NEVER FORCE THE GAUGE POINTER RIGHT ROUND AGAINST THE STOP.

5.6 Hydraulic system start-up

Connect port 1 coupling to either the cylinder or the motor. Ensure that any brake drum, inertia disc, motion transducer and force transducer connections are tight.

It is useful to be able to control the flow when supply pressure is applied. The control unit should therefore have power applied and be plugged into the servo unit.

If the supply hose or the fluid path of the servo unit contains any significant amount of air before starting, the hydraulic power unit should be "jog" started. This means turning on the supply for one or two seconds then turning it off for a similar period. This is repeated until most of the air has passed through the system, then the pressure is left on and allowed to build up to its full value.

If necessary, adjust the hydraulic power supply pressure to its correct value of approx. 70 bar (1000lb/in^2). See section 10.11.

The upper part of the port 1 hose may well have a certain amount of trapped air. If port 1 is connected to the motor, the offset control should be used to rotate the motor at a reasonable speed. This will rapidly flush out any trapped air. If port 1 is connected to the cylinder, the cylinder may be cycled repeatedly over its full stroke to pump out this air. This may be done with the offset control.

Note that when the cylinder is bolted to the force transducer, pumping is impossible. However, if port 1 pressure is cycled, the bubbles will be dispersed and slowly carried away by the leakage flow past the piston rings.

The remainder of the system is self-flushing. There is a small amount of air compressed into the gauge tubes but this is of no consequence.

The oil flowing through the return hose can be examined. When this is free from aeration the system is ready for use. (Continuous aeration may be a sign that the supply oil itself has become aerated, possibly because the reservoir level has fallen.)

This start-up procedure should always be followed.

Note that when the supply pressure is turned off, a check valve at the input to the filter prevents reverse flow. There is a considerable reservoir of high pressure oil in the accumulator, and if there is only leakage forward flow, this may take one or two minutes to dissipate.

5.7 Rotary transducer

To attach the rotary transducer assembly, remove the keepers from the magnetic feet. Align the input coupling with the motor shaft, attach the feet to the shelf and slide the unit towards the motor. Tighten the coupling by rotating the end cap with respect to the body.

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Plug the flying lead into the control unit socket.

When not in use, the magnetic feet should have the keepers replaced.

Note that the low-speed shaft of the gearbox is the correct diameter and height to accept the FEEDBACK digital shaft encoders.

5.8 Linear transducer

To attach the linear motion transducer, first remove the keeper from the magnetic foot. Position the foot on the right-hand side of the shelf, and lower the transducer coupling block down between the tie bars. Align the captive bolt in the block with the cylinder rod end. Screw the bolt home while holding the cylinder rod with a spanner across the flats. Never grip the cylinder rod itself, since the resultant scoring would ruin the rod seal.

Clip on the clear plastic guard and scale. See figure 1.

This guard must always be in place while the linear transducer is connected unless the supply pressure is zero. This is important, since finger-crushing forces equivalent to 200kg (450lb) are possible.

Note that, to aid measurement of the excursion of a rapidly oscillating rod, the thickness of the coupling block below the scale is 10mm.

5.9 Force Transducer

The force transducer is supplied fixed in position on the servo unit. If it becomes necessary to remove the transducer proceed as follows.

TURN OFF HYDRAULIC POWER AND REMOVE THE PORT 1 COUPLING.

Hold the flats of the cylinder rod with a spanner and loosen and spin the locknut up to the coupling nut. Unscrew the coupling nut from the force transducer. Depress the poppet valve in the quick-connect coupling when pushing back the cylinder rod. Unscrew and remove the transducer retaining bolt. Lift the transducer clear and lay it down alongside the servo unit. Unscrew and remove coupling from cylinder rod end.

Replace the force transducer by the reverse procedure. Again the hydraulic power must be off and the port 1 coupling disconnected.

5.10 Pressure and flow transducers

The two pressure transducers and the flow transducer are supplied fixed in position on the servo unit. If it becomes necessary to remove any of these transducers, the leads behind the panel should first be disconnected from the socket at the right hand side of the servo unit and drawn through to the front. The transducer may then be unscrewed and one of the 1/4" BSP plugs supplied in the accessory kit, inserted in its place taking care not to introduce any foreign matter into the system.

5.11 Transport lag hose

When the transport lag extension hose is used it is generally attached to the cylinder. To incorporate this extra length in the hydraulic path, mount the hose bracket to the motor/cylinder mounting plate with the screws provided, so that it rests on the top of the motor. Connect port 1 to the captive male coupling and take the loose female coupling to the cylinder input. See figure 2.

Drape the length of double hose either down the front of the bench on which the servo unit stands, or lay it along the base of the servo unit and through the front left-hand carrying handle. 160H-1d-1

If the hose contains air, it should be thoroughly flushed out by first connecting the hose to the motor (which is rotated) before connecting it to the cylinder. This cylinder connection again introduces a small amount of air which must be flushed out.

When not in use the hose ends should be coupled together to exclude dirt. Oil will automatically be retained in the hose.

5.12 Oil temperature

The oil temperature should not be allowed to exceed an indicated 40^{o}C. Above this the oil may become an inadequate lubricant. No portion of the hydraulic circuit should feel uncomfortably hot to the hand.

5.13 Heat exchanger

The exchanger fitted on the hydraulic power unit requires 3-5 litre/min (0.7 - 1 Imp. gal/min) flow of water for good performance. The water supply should of course be as cool as possible.

Conditions of usage will determine whether or not it is desirable to use the exchanger.

5.14 Control unit constants

Operating range of valve drive amplifier (in terms of operational amplifier output)	±2.0V
Offset control range (in terms of operational amplifier output)	±2.0V
Rotary velocity constant	26mV/rad/sec
Rotary position constant	500mV/rad (3.75V/rad on dial)
Linear velocity constant	10mV/mm/sec (254mV/in/sec)
Linear position constant	1V/mm (25.4V/in)
Pressure constant	100mV/bar (6.9mV/lb/in²)
Flow constant	8V/80% full scale
Force constant	2mV/newton (8.9mV/lbf)

(These are all nominal values)

Positive voltage on an input to the operational amplifier yields positive differential pressure (port 1 - port 2) from valve.

Positive differential pressure produces positive motion and torque/force.

Positive rotation and torque correspond to clockwise rotation of the motor when viewed from its shaft end. This gives clockwise rotation of the synchro transformer dial.

Positive linear motion and force correspond to the cylinder rod extending.

All positive actions yield negative transducer signals to give the correct polarity of feedback.

Flow measurement is in the system return line, and is therefore independent of the direction of flow in port 1. Flow transducer signals are always negative.

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In general, any application that requires a large force to be applied smoothly by a small actuator is a candidate for hydraulic power. Additionally, hydraulic power is the logical choice in certain other areas.

To name a few areas of application: hydraulic presses, earth-moving machinery, vehicle transmission, silent pile-drivers.

In many cases hydraulic power is applied in a closed-loop system. That is, the effect of the application of power is monitored and the pressure or flow adjusted automatically to give the required result. Examples of such closed-loop systems (or servomechanisms) are in rudder and stabilizer control on ships and the positioning of control surfaces in aircraft. One of the most rapidly expanding uses of hydraulic power is for the closed-loop control of machine tools. Typically, the work table is moved hydraulically at the command of a punched-tape program.

The three common power systems in use today are hydraulic, electrical and pneumatic. Because of the compressibility of the working fluid, most practical closed-loop systems would be very difficult, in many cases impossible, to mechanise pneumatically.

This leaves the choice between hydraulic and electrical power systems. Their relative merits are summarised below in a very general fashion. These generalisations are limited to power outputs above 50 watts, below which the advantage usually lies with a d.c electrical system.

MOH-19-2

Type of power	Hydraulic	Electrical
Actuator size	small	large
Speed of response of servomechanism	high	moderate
Linearity	often predominantly non-linear	usually predominantly linear
Cost of hardware	cheaper actuators and motors	
Weight of hardware (including power supplies)	comparable	
Reliability	generally higher	

Relatively simple hydraulic servomechanisms having a mechanical input, such as automobile power-assisted steering, may be entirely hydraulic. More sophisticated servo systems may require to follow an electrical input signal or to have complex frequency shaping in the feedback path. Mathematical operations on the feedback and forward paths are generally far easier to perform electrically than hydraulically. Therefore a logical combination in many cases is electronic feedback, signal summing, and amplification with a hydraulic power amplification output stage.

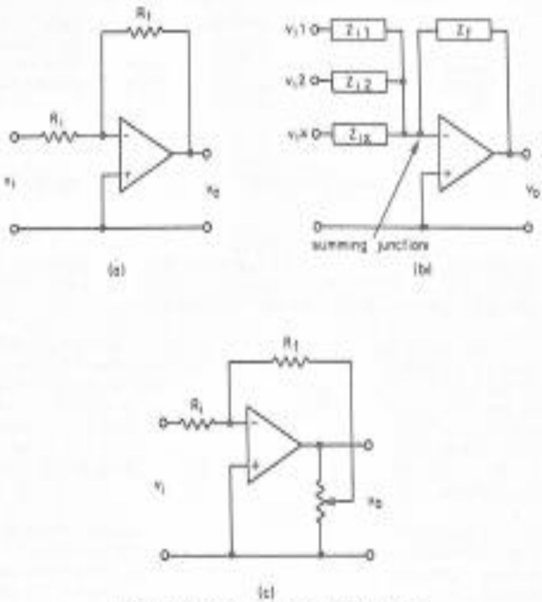

Fig 6 Operational amplifier configurations

560H-25

8.3 Valve drive amplifier

The valve drive amplifier converts the op-amp output voltage into a proportional drive current for the servo valve. The gain is 100mA/V. The full operating range of the valve output is ±200mA or, referred to the op-amp output, ±2.0V.

The INVERT switch inverts the valve drive amplifier input signal about ground.

The OFFSET control allows offsets to be introduced into the amplifier output. This may be used to compensate for the pressure bias required by the cylinder, to demonstrate the effect of offset in the forward path, or to provide simple open-loop control of the motor or cylinder.

A note concerning use of the valve drive amplifier to control ±600mA in an electric motor field will be found in Appendix B.

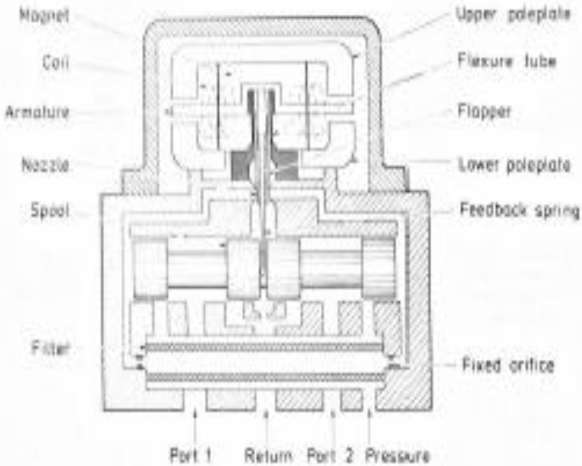

Fig 11 Electro-hydraulic servo valve

The flapper of the first stage hydraulic amplifier is rigidly attached to the mid-point of the armature. The flapper extends through the flexure tube and passes between two nozzles, creating two variable orifices between the nozzle tips and the flapper. The pressure controlled by the flapper and nozzle variable orifice is fed to the end areas of the second stage spool.

The input signal induces a proportional magnetic charge in the armature and causes a deflection of the armature and the flapper. This assembly pivots (in the plane of the paper in figure 11) about the flexure tube, increasing the size of one nozzle orifice and decreasing the size of the other. This action creates a differential pressure from one end of the spool to the other and results in spool displacement. The spool displacement causes a torque in the feedback wire which opposes the original input signal torque. Spool movement continues until the feedback wire torque equals the input signal torque.

Servo valves may be either 4-port or 3-port. In a 4-port valve, both output ports are used to give a push-pull drive, while a 3-port valve has only a single output port. Generally, a 4-port spool valve, such as that on the EHS160, may be used as a 3-port valve by simply connecting to one of the output ports and closing off the other.

The analysis that follows is generally of the 4-port configuration. The application to 3-port usage is discussed in section 8.6.5.

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